Work Distribution in
Global Product Development Organizations

by

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

The evolution of the internet, digital design tools, and more importantly, increasing access to global markets and workforce, has increased the interest of firms in offshoring their engineering and product development activities. However, there exist challenges in coordinating and collaborating across time zones, cultures, geographical locations, and organizations. These challenges are magnified in the case of firms engaged in the design and development of complex engineered products. Our field study of the global engineering efforts of five firms showed that offshoring success is largely affected by the choice of the offshoring content, the architecture of the firm’s products, and the organization choices of the respective firms. This led us to frame our research questions as: How does a firm optimally structure the global work distribution, over time, of its product development organization? How does the firm’s architecture affect these work distribution decisions?

Arguing based on existing literature in operations management, product development, and organizational economics, we identify coordination effort required between locations as a key contributing factor towards the performance of global product development organizations. We segregate the time required to complete a product development task between work time and coordination time, and define the index of modularity for offshoring as the ratio of the work time to the sum of work time and coordination time. We incorporate this factor to develop a recursive equation model that identifies the global structure (work distribution) of a product development organization.

We apply our model to structure (optimize) the global product development organization in an industrial setting (with the aim of minimizing costs). We use the design structure matrix (DSM) to map the current process flow. This DSM helps us identify the organization architecture that we can utilize in our optimization model. Our optimization results, based on detailed modeling of coordination costs, show significant cost savings through a re-structured PD organization. Subsequent analysis of our results shows that while offshoring based on modularity is generally right, it is not the whole answer as there exists a trade-off between the efficiency of performing specific PD tasks at the offshore location and the modularity of the task.

Besides relative cost rates and modularity, the optimal organization structure is also affected by the relative efficiencies in performing the product development tasks
across locations, leading to additional research questions: How does the task completion time change (efficiency differences) when a PD task is transferred to an offshore product development center? How are the firm’s prioritization and distribution of efforts towards the offshored PD tasks affected by the various factors that affect the task completion time?

To understand these efficiency differences and address the above questions, we develop and analyze a stylized model (two tasks, two locations, two time periods) for a firm seeking to establish a product development center at an offshore location to benefit from cost savings. Our key results show that (a) firms should determine their offshore content to benefit from the existing knowledge base created by the prior offshored content and to create a knowledge base from which subsequent offshoring can benefit (indicating path dependent offshoring) rather than offshoring solely based on modularity; (b) efforts supporting offshoring should prioritize the coordination challenges between tasks at different locations before those between tasks at the offshore location; and (c) in an environment of high volatility of external factors, efforts should be prioritized to enhance the work time and coordination time efficiencies in the first (earliest) period.

Thesis Supervisor: Steven D. Eppinger
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It is a very satisfying moment to reach and write this page of the thesis. Though it comes very early in the thesis document, it is generally written only after every other part of the thesis has been completed! I consider it very important as it provides me the opportunity to acknowledge all those who have supported me in this effort. I have been tremendously lucky to have benefited and enjoyed from the insights, guidance and support of many outstanding people. Two of them stand out without whose support I would not have progressed anywhere in this endeavor: my advisor Steve Eppinger and my wife Sudha.

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# Contents

1 Introduction ................................................. 13

2 A System Architecture Analysis of GPD .......................... 17
   2.1 Literature Review ........................................ 18
       2.1.1 Global Product Development (GPD) .................... 18
       2.1.2 System Architecture .................................... 22
   2.2 Organizing GPD for CES .................................... 23
   2.3 GPD Case Studies ........................................... 26
       2.3.1 Danaher Motion Precision Systems Group (Dover): Task Off-shoring .............. 26
       2.3.2 Pitney Bowes Mailing Systems: Component Outsourcing ......................... 29
       2.3.3 Microprocessor Development at Intel: Captive Global Engineering .................. 32
       2.3.4 Cessna Aircraft: Supplier Co-Development ........................................ 36
       2.3.5 Honeywell-Aerospace Division: Task Based Offshoring .............................. 39
   2.4 Summarizing the Case Studies ................................ 42
       2.4.1 Why do firms do GPD? .................................... 43
       2.4.2 Organization forms ....................................... 44
       2.4.3 Architecture decompositions ................................ 44
   2.5 Key Learnings from Case Studies ................................ 46
       2.5.1 Ownership Implications for GPD ................................ 46
       2.5.2 Implications for Architecture Decomposition for GPD .............................. 48
       2.5.3 Learning to do GPD ........................................ 49
   2.6 Direction for Future Research and Conclusion .................. 50

3 Optimal Structuring of GPD Organization. ......................... 55
   3.1 Introduction .................................................. 56
       3.1.1 What is Global Product Development? .................................. 56
       3.1.2 What are Complex Products/Systems? .................................. 57
   3.2 Theory and Model Development .................................. 58
       3.2.1 OM/PD/Organizations Approach .................................. 59
       3.2.2 Transaction Costs Approach .................................. 60
3.2.3 Theory Setup ........................................ 61
3.2.4 Model Development .................................... 62
3.3 Organizing GPD at Nokia ................................. 65
3.3.1 Problem Definition .................................... 66
3.4 Data Development ....................................... 68
3.4.1 Cost Data ........................................ 70
3.4.2 Efficiency Differences ................................. 70
3.4.3 Learning Effects ..................................... 72
3.4.4 Current State \(( t = 0 )\) Work and Coordination Time .. 73
3.5 Model and Results ....................................... 74
3.5.1 Problem Formulation .................................. 74
3.5.2 Optimization Constraints ............................... 77
3.5.3 Optimization Results .................................. 78
3.5.4 Observations ........................................ 78
3.6 Sensitivity Analysis ..................................... 83
3.6.1 Capacity Change Constraints .......................... 83
3.6.2 Learning Rate at GPD Location \( k = 6 \) ............... 86
3.6.3 Manpower Rate at GPD Location \( k = 6 \) .............. 86
3.7 Robustness of Methodology ............................... 88
3.7.1 Coordination time ................................... 89
3.7.2 Coordination efficiency ............................... 89
3.8 Challenges and Limitations ............................... 90
3.9 Conclusion ............................................ 90

4 Effort Distribution in GPD .................................. 93
4.1 Introduction ............................................ 93
4.2 Model Development ..................................... 95
4.2.1 Dynamics of Work Time ............................... 96
4.2.2 Dynamics of Coordination Time ........................ 97
4.2.3 Problem Formulation .................................. 98
4.3 Model Analysis ......................................... 99
4.3.1 Simultaneous Offshoring .............................. 100
4.3.2 Sequential Offshoring ................................ 102
4.3.3 Interactions with Home Location ...................... 103
4.4 Uncertainty and Risk Averse Firm ....................... 106
4.4.1 Uncertainty in GPD Location’s Learning Capability .. 106
4.4.2 Innovative systems ................................... 107
4.4.3 Exchange Rate ....................................... 109
4.5 Discussions ........................................... 110
4.6 Conclusion ............................................ 114
## CONTENTS

5 Conclusion ............................................. 117
5.1 A Process for Global Product Development ............. 118
5.2 Conclusion .............................................. 121

A Nokia Example: Formulae and Table ................... 123
A.1 Derivation of Learning Rate Formulae .................. 123
A.2 Learning Rate at Nokia .................................. 124
A.3 Coordination Efficiency Table .......................... 124

B Proofs for Stylized Models ............................. 127
B.1 Proof of Result 1: ....................................... 127
B.2 Proof of Proposition 1: .................................... 129
  B.2.1 Modularity ........................................... 129
  B.2.2 Learning by Doing Something Else ................ 129
  B.2.3 Learning by Repeated Doing ....................... 130
  B.2.4 Offshoring Penalty .................................. 130
B.3 Proof of Result 2: ....................................... 130
B.4 Proof of Proposition 2: .................................... 132
  B.4.1 Modularity ........................................... 132
  B.4.2 Other Parameters ..................................... 133
B.5 Proof of Proposition 3: .................................... 134
B.6 Proof of Proposition 4: .................................... 135
B.7 Proof of Proposition 5: .................................... 137
B.8 Proof of Proposition 6: .................................... 139
B.9 Proof of Proposition 7: .................................... 140
B.10 Supplementary: Two Stage Investment .................. 143
  B.10.1 Supplementary ...................................... 144
List of Figures

1-1 Product Development Process for Complex Systems .................. 14
1-2 Sourcing-Location Matrix ........................................ 15
2-1 Research in Global Product Development .......................... 18
2-2 Simple and Complex Engineered Systems .......................... 22
2-3 Offshoring Difficulties ........................................... 24
2-4 Global Product Development Architecture .......................... 25
2-5 Danaher Motion Process-based DSM ............................... 26
2-6 GDC Flexible Workforce (number in brackets indicates number of dedicated project engineers) .......................... 27
2-7 Danaher Motion Product-based DSM ............................... 28
2-8 Schematic of MEGA Midjet Series Mail Processing Module ........ 30
2-9 MEGA Midjet Series Architecture-Based DSM ...................... 31
2-10 Intel: Specialization by Site ...................................... 32
2-11 Intel: Microprocessor Design and Development ................... 33
2-12 Intel: Design and Development DSM ................................ 34
2-13 Intel: DSM Summary ............................................... 35
2-14 Typical Aircraft Sections ......................................... 37
2-15 Cessna: System Architecture based DSM .......................... 38
2-16 Honeywell: Task-Based DSM (Structure) ......................... 41
2-17 One Section of Honeywell DSM ................................... 42
2-18 Sample DSM cutout .................................................. 43
2-19 GPD Considerations .................................................. 44
2-20 GPD Approaches ..................................................... 45
2-21 Architecture Assessment and Type of Interface .................... 46
2-22 Summary Observations of Case Studies ............................. 47
2-23 GPD Ownership by GPD Consideration ............................. 48
2-24 Architecture Decomposition by GPD Consideration ................ 49
3-1 Nokia Product Development Process .................................. 66
3-2 Process DSM for Nokia High-End Devices Division PDD Process .... 69
3-3 Work Time and Coordination Time for PDD Process Tasks (units: man-years) .................................................. 70
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>Organization (department) nDSM (units: man-years)</td>
<td>71</td>
</tr>
<tr>
<td>3-5</td>
<td>Work Time Relative Efficiencies (at time t=0)</td>
<td>71</td>
</tr>
<tr>
<td>3-6</td>
<td>Coordination Time Relative Efficiencies (at time t=0)</td>
<td>72</td>
</tr>
<tr>
<td>3-7</td>
<td>Organization (department and location) nDSM</td>
<td>74</td>
</tr>
<tr>
<td>3-8</td>
<td>Data Development Methodology</td>
<td>74</td>
</tr>
<tr>
<td>3-9</td>
<td>Optimization Results (cost savings from S0 case)</td>
<td>78</td>
</tr>
<tr>
<td>3-10</td>
<td>Analysis of cost reductions</td>
<td>79</td>
</tr>
<tr>
<td>3-11</td>
<td>Work assignment changes at locations over time</td>
<td>81</td>
</tr>
<tr>
<td>3-12</td>
<td>GPD content over time (for each department)</td>
<td>82</td>
</tr>
<tr>
<td>3-13</td>
<td>Active capacity constraints</td>
<td>83</td>
</tr>
<tr>
<td>3-14</td>
<td>Sensitivity analysis of capacity constraints at Loc k = 2,3,4,5</td>
<td>84</td>
</tr>
<tr>
<td>3-15</td>
<td>Sensitivity analysis of capacity constraints at GPD Loc k = 6</td>
<td>85</td>
</tr>
<tr>
<td>3-16</td>
<td>Sensitivity analysis with new capacity constraint at Base Loc k = 1</td>
<td>86</td>
</tr>
<tr>
<td>3-17</td>
<td>Sensitivity Analysis of Learning Rate at GPD Loc k = 6</td>
<td>87</td>
</tr>
<tr>
<td>3-18</td>
<td>Sensitivity Analysis of Manpower Rate increases at GPD Loc k = 6</td>
<td>88</td>
</tr>
<tr>
<td>4-1</td>
<td>Work time changes with offshoring</td>
<td>97</td>
</tr>
<tr>
<td>4-2</td>
<td>Offshoring Prioritization between Modularity and Knowledge Creation</td>
<td>112</td>
</tr>
<tr>
<td>5-1</td>
<td>Thesis Summary</td>
<td>117</td>
</tr>
<tr>
<td>5-2</td>
<td>Decision Steps for GPD Content</td>
<td>118</td>
</tr>
<tr>
<td>5-3</td>
<td>A Process for GPD</td>
<td>120</td>
</tr>
<tr>
<td>A-1</td>
<td>Relative Coordination Efficiency (between locations)</td>
<td>124</td>
</tr>
<tr>
<td>B-1</td>
<td>Work time changes with offshoring</td>
<td>143</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The subject of global product development (GPD) is generating a lot of interest. Firms pursue GPD either to meet global market needs (locations other than home location) or to seek efficiencies. The drive towards GPD has been influenced by competitive pressures (pricing targets driving aggressive cost targets), availability of exceptional talent overseas, advances in communication that facilitate seamless information flow, intellectual property protection, and growing external markets. However, developing products across geographical boundaries presents significant challenges in coordination, communication, differences in culture, different time-zones, etc. (Fine (1998), Srikanth and Puranam (2008a), Anderson et al. (2008)). Hence, selection of development tasks that are to be offshored is very important.

The selection of these development tasks is further complicated in the case of complex engineered systems (CES). Such systems comprise of a number of components and processes with inter-dependencies during development. Development of CES comprises of system architecture development, followed by component development, and finally system integration (Fig. 1-1) (Ulrich and Eppinger (2004)). During system architecture development, the constituents of the system and their respective interdependencies are planned and their respective performance requirements specified. Components are then developed within the architecture established during system development. Finally the respective development efforts are collected and tested, during system integration, for adherence to the specifications developed during system architecture development.

Modularity, ‘a plan for organizing work by task partitioning and specifying standardized interfaces between them’ (Srikanth and Puranam (2008b)), is an approach proposed by many. Though modularization provides an opportunity to address these issues to some extent (Baldwin and Clark (2000), Anderson et al. (2008)), most engineered products (automobiles, aircraft, complex assemblies, etc.) require significant interactions between systems, sub-systems, components, etc. during design and development. These interactions identify the coordination that is required between the systems, sub-systems, components, etc. towards successful product development, im-
plying ‘limited’ modularity (Sosa et al. (2007)) which makes it difficult to identify components/processes that can follow the ‘modularity’ based concept for offshoring (Baldwin (2007)). Managing these coordination needs across locations is challenging. Thus, it becomes necessary to identify and prioritize the components/processes for offshoring and within this prioritized set, determine how the offshoring efforts need to be distributed.

Early research (1990s) primarily concentrated on research or on turnkey development. Collaborative development, whereby different processes or components of the product are developed in dispersed parts of the world, is now receiving increasing attention. Eppinger and Chitkara (2007) defined GPD as combining certain centralized functions with some engineering and related product development (PD) functions distributed to other sites or regions of the world - the practice may involve outsourced engineering work along with captive offshore engineering facilities. On similar lines, Anderson et al. (2008) refer to distributed product development (DPD) as the use of organizational arrangements involving multiple organizations that are separated by firm, geographical, or other boundaries, that are used for product development. Besides cost benefits, firms seek access to technical expertise, knowledge of global product needs, and flexible PD resource allocation through GPD.

From the above definitions of GPD and DPD, we infer that GPD is an organization arrangement which identifies the location and ownership of the PD activities. Since these activities can be distributed in various locations globally, it involves offshoring wherein some PD activities are done in a different country/continent. Compared to offshoring which is determined by the location at which the PD task is performed, outsourcing involves the ownership (make/buy) decision wherein responsibilities for certain PD tasks are transferred to another firm. This decision is driven, amongst other considerations, by the incentive structure agreed upon by the firms. An offshore PD center can be captive or supplier owned. Similarly, a supplier’s PD center can be onshore (similar location as the firm’s home PD center) or offshore (Fig. 1-2).

We (Tripathy and Eppinger (2007)) studied the GPD efforts of five firms (chapter 2). Though each firm had its own peculiarity, their GPD efforts had a relationship with the product, process, or organization architecture of the firm. The firm’s architecture helps in the identification of the product, process or activity (referred to as
task hereafter) for offshoring by recognizing the interface/coordination requirements. Firms engaged in the development of such complex products need to first define the set of tasks for offshoring. Thereafter, they need to identify the sequence in which these tasks/set of tasks are offshored and the proportionate allocation of support efforts to ensure that the objectives of offshoring are met. This leads us to frame our research questions as:

- *How does a firm optimally structure the global work distribution, over time, of its product development organization?*

- *How does the firm's architecture affect these work distribution decisions?*

We develop a general theory to address the above research questions *(chapter 3).* We do so for a firm whose GPD intent is cost savings. We discuss the applicability of this theory for firms that pursue GPD for other reasons subsequently. The first step involves identification of the trade-off criterion that would help address the above questions. The trade-off criterion in this case involves reduced cost rates at the new GPD location vis-a-vis higher time to complete the task. A key challenge in CES (focus of our study) is the significant coordination required between individuals and groups involved in the development of tasks that need to interact. We segregate the development time taken by a task (task time) into the time taken to do the assigned work (hereafter called work time) and the time required to obtain information for or to provide information from the assigned work (hereafter called coordination time). We use this segregate to develop the recursive equation model that identifies the optimal global work distribution for a firm's product development organization. The relative proportion of task time and coordination time in the total development time plays a critical role in the trade-off decision regarding GPD (Gomes and Joglekar (2008)). We define this ratio (work time divided by sum of work and coordination time (task time)) as the modularity of the component/process/task, a measure of the firm's architecture.
We apply the model in an industrial setting to design an efficient GPD organization. We use the design structure matrix (a tool used to study dependencies) to map the organization architecture, which helps us to distinguish between the work time and the coordination time between the departments. We formulate the example as an optimization problem and solve it for different scenarios and perform sensitivity analysis. We see that the coordination time cost component of total costs reduces more significantly than the work time cost component. This observation would imply that offshoring prioritization is based on the modularity index. However, we also observed a non-monotonic behavior: offshoring content to the GPD center is non-monotonic with respect to modularity. On analysis of the results, we observe that besides relative cost rates and modularity, the organization structuring is also affected by relative efficiencies in performing the product development tasks across the locations. This leads to an additional research question:

- *How does the task completion time change (efficiency differences) when a PD task is transferred to an offshore product development center? How are the firm’s prioritization and distribution of efforts towards the offshored PD tasks affected by the various factors that affect the task completion time?*

We develop a stylized model to study this research question (for a captive offshore product development center): chapter 4. We identify and incorporate the various factors that influence the offshoring decision in this model. These factors contribute to the relative work and coordination efficiencies. We study their individual and joint (with modularity) impact on the offshoring decision. We observe that a firm should prioritize those tasks that develop the competence/knowledge at the offshoring center rather than offshoring solely based on modularity. This contributes in the learning process of the subsequent tasks that are offshored. However, it also represents a trade-off between the long-term (knowledge development based) and short-term (modularity based) benefits that the firm needs to understand and decide on. Prioritizing offshoring tasks to develop competence/knowledge leads to path-dependent offshoring.

We summarize in chapter 5 by proposing a method that firms engaging in GPD can follow. We also outline emerging research questions from this research.
Chapter 2

A System Architecture Analysis of Global Product Development

Chapter Abstract: Recent advances in engineering collaboration tools and internet technology have enabled firms to distribute their product development (PD) tasks to offshore sites and global outsourcing partners while still maintaining a tightly connected process. In this research, we explore these global PD structures from process flow and system architecture perspectives, employing the design structure matrix method. Through five case studies spanning electronics, equipment, and aerospace industries, we observe the interaction complexity inherent in various global work distribution strategies; the complexity a combination of the PD structure and the specific strategy used by the firm. Our observations lead to implications for organization forms and architecture decompositions for firms pursuing offshoring of engineering activities. We conclude with potential research directions on the subject of global product development.

Introduction: As introduced in chapter 1, there is growing interest in the subject of global product development (GPD). Firms are driven towards GPD either due to competitive pressures, or are attracted by overseas market opportunities and overseas talent. Further, advances in communication technologies and availability of intellectual property protection have aided the process. However, at the same time, there is a lot of concern on where to do GPD, and more importantly, how to do GPD. In this chapter we study the GPD approach and experiences followed by five firms in engineering and high-technology industries. We use system architecture principles, utilizing the design structure matrix (DSM) tool.

We first provide a brief survey of existing literature on global product development, tracing it from when global efforts were concentrated on research or turnkey development to now when firms look to develop products through teams located across locations. We combine the two streams of literature to develop our thoughts on organizing GPD for CES as a prelude to the case studies (section 2.2). Our case studies follow in section 2.3. We collate our findings from the field studies, from organization
and architecture viewpoints (section 2.4), deriving some key learnings (section 2.5). We conclude with some thoughts on GPD and directions for future research (section 2.6).

2.1 Literature Review

2.1.1 Global Product Development (GPD)

Past studies in the area of global research (global R&D) have primarily focussed either on research or turnkey development. Collaborative development, whereby different processes or components of the product are developed in dispersed parts of the world, is now gaining increasing attention as a research topic. Eppinger and Chitkara (2007) outlined the benefits of GPD to include greater engineering efficiency (through utilization of lower cost resources), access to technical expertise that is distributed internationally, design of products for more global markets, and more flexible PD resource allocation (through use of outsourced staff). We capture the evolution of academic literature in the area of global product development in Fig. 2-1.

<table>
<thead>
<tr>
<th>Research / Turnkey Development</th>
<th>Global Product Development</th>
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<tr>
<td>Govt. controls, closed markets, limited IT/bandwidth</td>
<td>Open markets, collaborative tools/bandwidth</td>
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<tr>
<td><strong>Research</strong></td>
<td><strong>Turnkey Development</strong></td>
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<td><strong>upto mid 90s</strong></td>
<td><strong>from mid 90s</strong></td>
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Figure 2-1: Research in Global Product Development

Academic literature is rich in the study of global R&D, virtual teams, distributed development, etc. Kummerle (1997) differentiated global R&D sites between those that are home-base augmenting and those that are home-base exploiting. The home-base augmenting R&D sites absorb knowledge from the global scientific community, create new knowledge, and transfer it to the company’s central R&D site. In contrast, home-base exploiting R&D sites commercialize knowledge by transferring it from the company’s home base to the laboratory site abroad, and from there to local manufacturing and marketing. Gassmann and von Zedtwitz (2002) further defined four archetypes of R&D internationalization -
2.1. LITERATURE REVIEW

1. national treasure, where both research and development are done domestically
2. technology-driven, where development is domestic and research dispersed
3. market-driven, where research is domestic and development dispersed
4. global R&D, where both research and development are dispersed

Companies would normally start from type 1. and then proceed, through either 2. or 3., to 4. global R&D. In contrast, Chiesa (2000) had associated foreign-based R&D laboratories with two structures - specialization based (where the laboratory has full global responsibility for a product or technology or process) and integration based (where different units contribute to technology development programs). These integrated R&D laboratories with their networks do get involved in GPD in terms of the definition provided by Eppinger and Chitkara (2007).

Beyond defining global R&D and GPD, it is imperative to understand why these efforts are undertaken, how these efforts are undertaken, and what challenges and issues arise in these efforts. GPD is gaining prominence for many reasons (Eppinger and Chitkara (2007)), chief among which are leveraging lower costs, improved processes available on account of focus on design for manufacturing (1980s) and reduced time to market (1990s), global growth in markets requiring instant access to market, and availability of integrated PD processes (leveraging on advances in digital and networked technology) that include engineers in regions where critical new technology has been developed.

Coupled with the ‘why’ is the ‘where’ to do GPD question. Kumar (2001) studied the determinants of location of overseas R&D in multinational enterprises of US and Japanese origin and found that the key factors favoring location of overseas R&D were large domestic market, abundance of low-cost R&D manpower, and scale of national technological effort. A significant proportion of the studied firm’s R&D activities followed that of leaders in their own fields. Further, lack of patent protection or restrictive trade regime affected the attractiveness of a country which was otherwise suited for R&D expansion. He also noticed that Japanese firms’ R&D abroad was more in low-tech products.

Through their study of Japanese, European and US based multinational enterprises, Bas and Sierra (2002) found that companies decided on investing in R&D after comparing relative advantages of home and host countries. The key strategies followed fall into four broad types -

- technology seeking, where the company tries to offset home country weakness in a given technological field by selecting a host country with proven strength in the technology
- home base exploiting, where the technology is created at home but then adapted in the foreign location to exploit the market
• home base augmenting, where the technology base is strong in the company at home and at the host and the idea is to acquire knowledge from the host

• market driven, where the technology base is weak both at home and at host

National market importance, local considerations like government incentives, and modes for implementation (greenfield, joint-venture, foreign acquisition, global matrix structure) are also influencing factors that contribute to the identification of R&D locations (Julian and Keller (1991)).

The key issues that academic literature has addressed with respect with global R&D relate to how to manage the R&D sites and issues regarding culture/teams/communication. Hakonson and Zander (1988) studied the internationalization of R&D efforts of four Swedish companies and concluded that a strategic balance is required in managing the R&D sites. Corporate R&D needs to carry out the central task of acting as liaison between the R&D organization/sites with corporate management (to ensure conformance of R&D to corporate objectives), facilitate communication within the group, develop common standards, etc. Detailed R&D needs to be conducted and tracked by divisional R&D departments, who will coordinate worldwide efforts of the products. The line responsibility should lie with individual country/market leads. Graber (1996) in his discussions on global R&D efforts of Black & Decker’s Worldwide Household Division, identified the global business team structure as a very important ingredient to GPD, along with top management commitment. Other factors critical to the success of global R&D efforts include steps to prevent leakage of information, managing government policies and political risks (Julian and Keller (1991)), and the need for adequate networking (Pearch and Papanastassiou (1996)). Asakawa (2001) discussed managing the organizational tensions prevalent in global R&D. He has used perception gap as a primary manifestation of organizational tension within a firm and claims that this gap occurs due to two main reasons - information sharing issues and autonomy related issues.

The other big challenge with global R&D and hence with GPD is with the global teams - how will they operate, will they be able to work together, and what will be the methods/modes for communication and information sharing. deBrentani and Kleinschmidt (2004) identified four scenarios for international product development - positive balanced, hands-off approach, no budget for international PD and high involvement only. They suggested that the scenario adopted played an important contributory role towards the success of international PD efforts. The best performers needed to be positively balanced, required a strong innovation-plus-globalization culture for PD, solid top-management involvement, and sufficient resources to support the program. However the biggest problems faced with global teams are social and cultural (Kahn and McDonoughIII (1996)) - communication, interpretation, promoting trust, getting over the not-invented-here syndrome. The key challenges for a global NPD team leader are therefore both interpersonal (trust) and programming (program milestones, tracking, responsibilities, resources) (Barczak and McDonoughIII (2003)).
2.1. LITERATURE REVIEW

Barczak and McDonoughIII (2003) further advise that the global NPD teams should meet initially for at least 3 days, to increase the amount and quality of communication, and hold periodic progress meetings. Cedrone and McDonoughIII (2000) suggest that individuals have a strong desire to perform well in the eyes of other members of the peer group and it may be advisable to allow them to choose their tasks/work through which they may want to contribute. Managing communications is a crucial task of the team leader. However, another study has found that virtual teams can be just as effective without ever meeting in person (Cummings (2004)).

Yet another branch of literature deals with knowledge transfer in global R&D networks. In particular, tacit knowledge has been studied, which is difficult to measure or monitor for transfer. Subramaniam et al. (1998) observed that European and US based multi-national enterprises seemed to employ cross-national PD teams and use overseas subsidiaries as sources of new product concepts when knowledge about different product design requirements among overseas markets or plants is tacit. Subramaniam and Venkatraman (2001) studied NPD capability and tacit overseas knowledge, and concluded that companies that harness greater tacit insights about overseas markets are more likely to have greater transnational NPD capabilities. Tacit knowledge ‘indwells’ in minds of people of an organization, and the inherent difficulties in its codification and communication pose significant barriers to the replication of the same by rival organizations, and hence, it is an important strategic resource. Subramaniam (2006) concluded, from his survey of 45 MNCs (90 responses) involved in manufactured goods, that instead of cross-national teams or cross-national communication, cross-national collaboration is more effective in new product development. Cross-national collaboration involves the collaboration of the home organization and its offshore development center in pricing, planning new products and programs, competitive analysis and product (involving effective transfer of embedded knowledge) and enhances the embodiment of embedded knowledge into the product.

Though most of the global R&D or GPD studies have reflected on why they should be done, the challenges faced therein, etc., they have not addressed the key issue of how it should be done. This issue has not been clearly addressed even by recent studies (Eppinger and Chitkara (2007), Anderson et al. (2008), Gomes and Joglekar (2008), Sosa and Mihm (2008)) that have called for product development to be organized through GPD organizations, where systems/components/processes of product development are carried out simultaneously across the globe. Most of these studies assume that it is possible to transfer the complete responsibility of the product or the process to a global site (implying that there exist modular content that can be transferred). Such an assumption may not hold in the case of complex products which are developed by teams whose strength may be in hundreds or thousands. In such cases a proper system architecture analysis is needed to understand the product or process, and then identify the suitable content for offshoring.
2.1.2 System Architecture

CES (Fig. 2-2) are networks of components that share technical interfaces to function as a whole (Sosa et al. (2007)). They have behaviors and properties that no subset of their elements have (Whitney et al. (2004)). CES generally comprise of a large number of components. In such cases, a hierarchy can be established wherein the product or system is decomposed into sub-systems, and those sub-systems are further decomposed into components. There could be more than a single level of sub-system decomposition before arriving at the component level. The system is then defined as a set of different elements connected or related so as to perform a unique function not performable by the elements alone (Rechtin and Maier (2000)). The sub-systems within the system and the components within a sub-system are interconnected or dependent on each other and these relationships define the system architecture.

![Simple System](image1.png) ![Complex System](image2.png)

Figure 2-2: Simple and Complex Engineered Systems

Complexity of a system is defined by the complexity of the interconnections and/or the dependencies in the system architecture. The complexity of an architecture therefore relates to the structure - in terms of components, connections, and constraints - of a product, system, process, or element. Architecting is the process of creating and building architectures, mostly those aspects of system development most concerned with conceptualization, objective definition, and certification for use. System architecting has been defined (Rechtin and Maier (2000)) as the art and science of creating and building CES, the part of systems development that is most concerned with scoping, structuring, and certification. System architecting can be of two types - the art which is based on qualitative heuristic principles and techniques, and the science which is based on quantitative analytic techniques.

The architecture of a system can be looked at in many ways - product architecture, process architecture, organizational architecture, etc. Ulrich (1995) defined product architecture as the scheme by which the function of a product is allocated to physical components, driving the performance of the product, product variety, product change, etc. Further studies (Gulati and Eppinger (1996)) have shown that an intricate relationship exists between product architecture and organizational design, each relying upon and driving the other. Product architecture is reflected in the information flow system of the firm and any change in the architecture has the potential to destroy the
2.2. ORGANIZING GPD FOR CES

firm (Henderson and Clark (1990)). Process architecture can be defined as the set of tasks and the related information flow between them, that sum to produce the final product/system. Organizational architecture can be defined as the small sub-teams in a project involving the development of a system/product and the relationships, in terms of information flow, hierarchy, etc., existing between these sub-teams.

In a CES, it is very difficult to study, design, or source the entire system as one. Rather, as stated by Simon (1969), CES should be decomposed into sub-systems or models such that each module becomes a black box, hiding design details from other modules. So it becomes necessary to decompose the system. Often such decomposition is necessary to identify the cause of a problem, or to identify a level of sub-system/component that can be designed or outsourced, or a level at which a sub-team can be assigned responsibility. von Hippel (1990) suggests that firms should specify their tasks in order to reduce the problem-solving interdependence amongst them, by predicting which tasks are likely to be important new information sources and which tasks affect others.

Design structure matrix (DSM) can be a useful tool to represent the architecture of a system, either by product or by process or by team or as a hybrid of these. DSM (Steward (1981)) is a project modeling tool which captures the relationships between project tasks or sub-systems/components in a matrix form. DSM can be used in organizing tasks in product development (Eppinger et al. (1994)). DSM helps to first decompose the system (by product, process or as required) and then identify the relationships or information flow, if any, between these decomposed sub-systems, tasks, sub-teams. An extension of the DSM is the numerical DSM where numbers, either absolute or relative, are input into the matrix and help in making decisions.

2.2 Organizing GPD for CES

As evident from existing literature, there exists a gap on how GPD needs to be undertaken, i.e. what are the components or tasks or sub-systems that should be offshored. How does the offshored development work relate to the objective of pursuing GPD? What process does a firm try to follow in their GPD efforts? What are the results of their GPD efforts? The key to understanding a firm’s approach to GPD lies in two complementary theoretical constructs: (a) decomposition of interacting elements, and (b) difficulties in coordination across distances. We discuss the ‘decomposition’ approach to GPD in this section and observe the challenges of coordination across distances in the case studies in the next section.

It is rare for a firm engaged in the design and development of CES to offshore the complete set of activities. It may happen when it is to an offshore captive unit or the product is being supplied by an ODM. At times the design and development may be offshored (with outsourcing) to design houses, captive development centers, or engineering services firms, but these become rare as the complexity of the systems
CHAPTER 2. A SYSTEM ARCHITECTURE ANALYSIS OF GPD

increases. Rather a firm initiates the process of setting up an offshore development center (captive or supplier) by offshoring a set of tasks, with the expectation that this set would grow over time. Identification of these successive and sequential sets of tasks is challenging for CES due to the coordination needs required to ensure that appropriate information exchange takes place for successful product development (Clark and Fujimoto (1991), Wheelwright and Clark (1992)).

CES (Fig. 2-3) comprise of sub-systems which are made of components or tasks. At the component/task level, there can be a need for significant coordination needs during offshoring. Offshoring of a component/task that has coordination needs with another component/task that is at a different (home) location is difficult compared to offshoring of either a component/task that does not have these coordination needs or set of components/tasks that require coordination within themselves. However in some cases the firm may decide to go in for offshoring the component with coordination needs across locations when it may be seeking product competence and is unable to identify the necessary interfaces (Fujimoto (2002)) to eliminate coordination needs. Generally these happen with outsourcing where the supplier with the necessary competence happens to be offshore (a happenstance), e.g. Pitney Bowes (section 4) could identify the interface needs to ensure outsourcing to an offshore supplier Canon such that there were limited coordination requirements during component development.

![Figure 2-3: Offshoring Difficulties](image)

The above offshoring approaches can be classified into two types for CES: component offshoring and sub-system offshoring (Fig. 2-4). Each of these GPD organizational arrangements has its own benefits and challenges. While sub-system offshoring may ensure that coordination needs are controlled within a location, it could lead to loss of sub-system development capability at the home location. Similarly component development offshoring will require significant coordination across locations and can lead to inefficiencies.
2.2. ORGANIZING GPD FOR CES

In this study we review and critique the GPD efforts of five firms which are engaged in the design, development and manufacture of CES. Specifically, as outlined by papers on analysis of case studies (Eisenhardt (1989), Yin (2002), Eisenhardt and Graebner (2007)), we enquire why the firm undertook GPD, how the firm undertook GPD, and what were the results of the GPD efforts undertaken by the firm.

We analyze the GPD efforts of each firm using a system-architecture approach. Using existing theories and tools of system architecture, we study how each of these firms’ processes and/or products could be decomposed. We used this decomposition to understand the rationale for their GPD efforts. For firms following a process-based GPD approach, we analyze their task structure, the information flows between different processes, and the relationship between their process based architecture and GPD content. Similarly, for firms that used product decomposition, we analyze how the product is decomposed to sub-systems and parts, the existing interdependencies between the sub-systems/parts so defined, and the relationship between the product architecture and GPD content. In our final case study, we come across a firm that was in the process of setting up a new department and was looking at exploiting the labor cost differences between locations to staff the department. In such a case, the use of task decomposition to sub-tasks and the identification of co-ordination requirements between sub-tasks play a significant role in identifying the tasks that can be located offshore.

We use the DSM methodology to decompose the architecture (product/ process/ organization) of the firm and then understand the rationale for offshoring and/or outsourcing the relevant component/ task/ activity. We also use the DSM to initiate the process for identifying the structure of a new department.
2.3 GPD Case Studies

2.3.1 Danaher Motion Precision Systems Group (Dover): Task Offshoring

Our study was based at Dover, a unit of Danaher Motion’s Precision Systems group. This unit’s products were based on air-bearing based precision motion (linear and rotary). These products found applications in high performance machinery utilized in a wide array of industries including data storage, flat panel display, semiconductor lithography and wafer inspection, circuit board assembly, high precision assembly, and metrology. Due to its ability to develop customized solutions based on its core technology, this unit has a loyal customer base which values the quality, speed and agility with which their needs are addressed. In a typical scenario, Dover’s order to delivery timeline is just six months.

Dover’s short order-to-delivery timeline requires quick engineering turnaround, which in turn involves large groups of engineers working together to provide solution alternatives and rapid design iterations as well as concurrent design, engineering, and manufacturing process development. Many component designs are translated into production parts with no prototype production. The combined requirements of quick turnaround and customized products present a challenging proposition to Dover’s engineering staff whose experience has helped them to address these challenges. Product development at Danaher Motion followed a six-stage gate process. The duration of each stage gate varies by product and customer need. Decomposition of Dover’s product development process is shown in Fig. 2-5.

Figure 2-5: Danaher Motion Process-based DSM

Danaher Motion’s GPD efforts: Dover’s GPD efforts has evolved through two
of three planned GPD phases:

**Phase 1 Learning about Outsourced Engineering:** This unit outsourced and offshored certain process-driven engineering jobs such as drawings, detailing for manufacturing, CAD, etc. to an engineering service provider in India. These tasks needed to interact with other tasks (Fig. 2-5), most of which were performed inhouse at the home location. The offshore supplier was not able to meet the turnaround time requirements and Dover Motion had to transfer the responsibility of these tasks back to the home location.

**Phase 2 Setup of Global Development Center (GDC):** Danaher Motion then initiated a group initiative which required that all group companies offshore to another engineering service provider in India (much larger and providing a wider range of engineering services and solutions). This activity involved the setting up of a Global Development Center (GDC) with the service provider. Each unit in the group was assigned dedicated project engineers and a pool of engineers was created below them (Fig. 2-6). These project engineers were trained at the respective units and provided specific product-related expertise. In contrast, the pool of engineers were trained in general engineering skills which could be utilized across the units.

![Project Engineers (dedicated by unit)](image)

Dover, as a first step, offshored the same work content as *Phase 1*. They observed a significant difference in work turnaround and efficiency compared to *Phase 1*. This encouraged them to identify more tasks for offshoring to meet budget and efficiency targets. The process DSM (Fig. 2-5) was the appropriate tool to help identify the same.

**Phase 3 Increasing Utilization to Achieve Efficiency and Scale:** The next phase would require a higher level of involvement by GDC in the Precision Group’s product development efforts. This could involve the transfer of complete component or sub-system design responsibility. From the architecture-based DSM (Fig. 2-7), the control systems parts have limited interactions with other systems/parts. Hence, they could be considered for the next stage of offshoring. Other systems for offshoring include pneumatics and hydraulics of the basic structure. However, the design of
the axis carrying motion components, a core technology that needs extensive on-site collaboration, needs to stay in-house. Further, being a core competence related system, Dover would want to protect it for deliverable compliance. Subsequent to design and development offshoring, manufacturing offshoring could be reviewed.

![Figure 2-7: Danaher Motion Product-based DSM](image)

**Key Takeaway**: Due to the quick turnaround requirements of this unit, it is key to have constant communication between different design/engineering/functional groups to achieve time and quality requirements. The significant overlap between design, development and manufacturing activities requires engineers to be present on-site.

A key observation from this process is that GPD can easily be started with process-based offshoring; drawing, detailing, and CAD are fairly independent processes that can be offshored without much disruption. The related software and protocols are, most often, industry norms. There are also immediate cost and productivity benefits from offshoring. It may be difficult, however, to transition to offshoring component/sub-system design as doing so would require training and the benefits will not be visible until desired levels of efficiency are achieved. Moreover, a quick engineering turnaround company may not want to risk offshoring these responsibilities before confidence in the offshoring centre is achieved. The DSM architecture helps in identifying appropriate offshoring strategies.
2.3.2 Pitney Bowes Mailing Systems: Component Outsourcing

Pitney Bowes (PB) is a US$5.5 billion company based in Stamford, Connecticut. Its business encompasses global mail processing solutions, global business services and financial services. Over the years though PB has divested majority of its manufacturing facilities, production of certain core products that require technology, security or systems integration, has remained in-house. By nature of the mail business, product innovation and development at PB is driven by the postal requirements specified in various countries. PB has engineering centers in Shelton, Connecticut, and in UK and France.

Global Mailstream Solutions is PB’s core business. This business is responsible for all the equipment that PB designs and builds for inserting, sorting and weighing mail, and affixing postage. Traditionally, these machines included meters which had to be ‘loaded’ in post offices and subsequently, through the telephone for postal credit. In 2002, PB introduced Intelli-link, which allows customers to update postage credit online. Intelli-link represents a critical competitive advantage for the company. PB’s Global Mailstream Solutions business also offers various mailing and customer communication software solutions.

**The MEGA Mailing Systems:** In early 2001, as a response to the United States Postal Service’s new postal indicia requirements, the growth in IT and electronic media, and the availability of new IT infrastructure, PB began developing a new series of mailing systems: the MEGA Midjet Series and the MEGA Fastjet Series. The development of the new series followed certain guidelines:

1. Electronic exchange of data between customer mailing systems and PB through Intelli-link (e.g., download of postal credit with the required security, software updates, usage information flow back to PB).
2. Single UIC (user interface) part design, compatible across all MEGA series mailing systems.
3. Introduction of postal security devices (PSD, ASIC) as mandated by the postal department.
4. Development of a single print head/engine for all MEGA mailing systems.
5. Self-service mailing systems which would provide savings through a reduction of field service needs for both PB and the customer, e.g. the customer would be able to change printer cartridges and control features in UIC, etc.

**Product Architecture:** The MEGA mailing system was developed in two series: Fastjet (fully automatic with output of 260 envelopes/minute) and Midjet (semi-
automatic with output of 160 envelopes/minute). The Midjet Series comprises of three main modules as shown in Fig. 2-8: UIC, input, and finishing.

Figure 2-8: Schematic of MEGA Midjet Series Mail Processing Module

Pitney Bowes follows a five stage PACE product development system (McGarth (1996)). There is a lot of emphasis on upfront specification and feasibility development which helps them identify the different modules and the respective interactions and dependencies between them. This is shown in the product architecture based DSM (Fig. 2-9).

Global Product Development & Opportunities: While most components are produced by global suppliers, global engineering is limited to partial software development by China-based CIENET and printer development by Canon. Most of the other design and development is done inhouse except UIC’s flexi circuit design and the input module’s power supply unit.

However, the highly decomposable structure of the MEGA Midjet Series provides several opportunities for PB to further develop GPD. The company having responsibility for core design, manufacturing feasibility sign-off, and manufacturing, respectively, for each sub-system/part, has been identified in the architecture-based DSM (Fig. 2-9). Sec Vend against PSD implies that it is designed, studied for manufacturing feasibility, and manufactured by a second vendor, in addition to Pitney Bowes. Cherry, Brother, and Canon, are the key companies that support the design, manufacturing feasibility studies, and sub-system/part manufacturing efforts of the
2.3. GPD CASE STUDIES

MEGA Midjet mailing system.

While the design of the core technology and security components like PSD, MMC, ASIC, along with system integration will likely remain in-house, many of the other components or complete modules could be outsourced (to offshore suppliers) for design and development. The architecture-based DSM clearly shows that significant upfront effort is involved in designing the system architecture. The physical and information flow interfaces between the different modules are well identified during this phase, enabling the modules to be developed independently thereafter.

One opportunity involves software development (primarily in the UIC and the MMC), which is becoming a significant portion of MEGA Midjet Series' overall product development. While all software work related to feasibility studies, software architecture, and MMC, PSD, and ASIC software for the MEGA Midjet Series will likely remain in-house, there is a potential to expand the outsourcing of software development, which is currently limited to coding and testing work. With increased confidence in CIENET's competency and level of resources, more software development could be outsourced. With proper IP and security protection even non-critical security related software development could be outsourced (though the challenge of outsourcing part of embedded software remains).

A second GPD opportunity for PB involves outsourcing the design and development of the input module. The Brother affiliate Chinese manufacturer responsible for assembling the MEGA Midjet Series' input module could eventually be responsible for the module's complete design and development, since they are well known for their

Figure 2-9: MEGA Midjet Series Architecture-Based DSM
CHAPTER 2. A SYSTEM ARCHITECTURE ANALYSIS OF GPD

engineering capabilities. Design and development of the power supply unit could also be included, enabling a complete module design proposal. An alternate design for the power supply unit could feasibly emerge from this arrangement leading to greater cost savings for PB.

A third opportunity involves the design and development of the entire UIC module. With the exception of the PSD and PB chip, outsourced North American vendors (primarily Cherry) currently manufacture the entire module. However, considering that the UIC uses a number of standard parts, design and development for the module could feasibly be outsourced to vendors outside of North America.

**Key Takeaways:** The architecture-based DSM for PB's MEGA Midjet Series highlights how a product can be well partitioned by modules once the system architecture design has been completed. Such modular architecture can enable each module to be developed independently (out-shore/off-shore/in-house). It also provides an opportunity for manufacturing suppliers to vertically integrate to become design-cum-manufacturing suppliers, thereby offering synergy benefits.

### 2.3.3 Microprocessor Development at Intel: Captive Global Engineering

Intel designs, fabricates and sells microprocessors, in addition to other products. The design activities for microprocessors are based in several inhouse facilities in the United States and Asia/Europe. To enable collaboration and transfer of tasks, the design capabilities among the centers are similar, though specific system design capabilities for various types of microprocessors reside at respective locations (Fig. 2-10). For example, while one site specializes in desktop processors, another site specializes in high-end server microprocessors for industrial applications, and a third is dedicated to mobile microprocessors.

<table>
<thead>
<tr>
<th>Location of Center</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>“productization” of design</td>
</tr>
<tr>
<td>Oregon</td>
<td>desktop series microprocessors</td>
</tr>
<tr>
<td>Colorado</td>
<td>high-end microprocessor design</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>high-end microprocessor design</td>
</tr>
<tr>
<td>Israel</td>
<td>mobile technology</td>
</tr>
<tr>
<td>Moscow</td>
<td>under development</td>
</tr>
<tr>
<td>Bangalore</td>
<td>under development</td>
</tr>
</tbody>
</table>

Figure 2-10: Intel: Specialization by Site

**Microprocessor Design and Development:** The modern high-end microproces-
2.3. GPD CASE STUDIES

The processor is made up of two main parts: multiple cores supported by an uncore which provides the external interfaces. Microprocessor design and development follows a 4-phase process (Fig. 2-11): upfront global architecture definition, designs of each unit of the core and the uncore, complete chip integration, and finally, productization and manufacturing preparation.

Phase 1 Phase 2 Phase 3 Phase 4

Global Architecture

Core

Uncore

Chip Integration

Productionization & Manufacturing Preparation

Home Site Many Sites Home Site California Site

Figure 2-11: Intel: Microprocessor Design and Development

Although various Intel design facilities specialize in the architecture development of various types of microprocessors, capability to develop core or uncore units are general (rather than specific), and exist in each of the development facilities. As a result, project leaders are able to draw resources from any of the design facilities. If, for example, a microprocessor for mobile technology is being developed, the specialized design team is able to utilize resources from any of the other facilities based on need and availability. Intel regards such flexible resource availability for the design and development of its products as a competitive advantage.

Phase 1 of global architecture development consists of defining the architecture of the chip, the information flows between the different core and uncore units, and development of the unit architecture and unit floorplan of the various core and uncore units. During this phase, the team is co-located, usually at the home site specializing in the chip type. Thereafter, Phase 2 development could be done in two parts - one team could do the development up to behavioral code stage, and then another team could take over from circuit design till unit integration. Though it may be ideal for the members to be co-located with the project leaders, it is possible for them
to work from their respective facilities during this phase. In Phase 3, the designs of the various core and uncore units are integrated per the architecture developed in Phase 1. During this phase, it is necessary for the relevant team members to be co-located at the home site. The final phase, Phase 4, occurs at California site, where productization and manufacturing preparation of the design takes place. The key development facilities of Intel with their respective specializations are listed in Fig. 2-10.

**DSM Development:** It was recognized that a pure architecture-based or pure process-based DSM would not explain the relationship intricacies present during microprocessor development. Hence, an architecture-based DSM was first developed and then the key processes in the development of each of the units were added (Fig. 2-12). A section of the DSM has been expanded in Fig. 2-13. The relationships between various units/processes were then identified and quantified. Ratings of A, B or C were assigned based on the impact of one process on another process. Relationships that received an A rating would likely require a 50-100% revision of the upstream task, B, a 20-50% revision, and C, less than a 20% revision.

Figure 2-12: Intel: Design and Development DSM

A review of the relationships showed that most A ratings exist within the core
or uncore units. Moreover such high rework possibilities only existed during Phase 2 (unit design) and Phase 3 (chip integration). This can be deduced as a strength of Intel’s upfront global architecture development efforts (Phase 1), wherein the various unit design efforts are self-contained from Phase 2. This also provides an opportunity for the unit teams to work individually, and it is not necessary for the various teams to be co-located. The other A ratings occur during chip integration phase (Phase 3) when all the team members are co-located. There are no A ratings in Phase 3 that may require a review of any of the Phase 1 or Phase 2 activities.

There are a couple of A rated interactions/dependencies across units. However, these interactions occur during the unit architecture and unit floorplan part of design when the team is co-located. Hence, any big revision arising from these interactions/dependencies should be manageable. Similarly, most of the B rated interactions/dependencies occur, either, during Phase 1 or Phase 3 (when the team is co-located) or within the core and uncore units. Thus, they can be managed within co-located teams.

**Takeaways:** Some takeaways from the microprocessor DSM are:

- The formation of unit-based teams is obvious as most interactions/dependencies exist within the core or uncore unit after Phase 1.

- Significant efforts in Phase 1 (approx. 50% of the microprocessor design time) ensure that units can be developed independently thereafter, till the final phase of chip integration (Phase 3).

- During Phase 2, individual unit teams can continue design work independently, and need not be co-located with other teams. This gives Intel the flexibility of using resources from different design centers for different unit designs. This is a very useful flexibility to have when a firm is looking to balance workload.
Chip integration (Phase 3) does require the team to be co-located. However, the total team strength is quite reduced at this phase since limited representation from the respective unit teams would suffice.

2.3.4 Cessna Aircraft: Supplier Co-Development

Cessna Aircraft (Cessna) is the world’s leading designer and manufacturer of light and mid-size business jets, utility turboprops, and single engine piston aircraft. It is part of the $10 billion Textron group, and is headquartered at Wichita, Kansas, where it also has its main manufacturing facility, and engineering and product development center. Additional manufacturing facilities are located at Independence, Kansas and Columbus, Georgia. Cessna’s aircraft design and development activities are vertically integrated; with most design efforts for aerodynamics, structures, and systems integration and most product-level testing being carried out in-house.

A First Attempt at GPD (Supplier Co-Development): Cessna’s first attempt at GPD was based on a realization that, going forward, it would be challenging to do all design work in-house. Cessna decided to experiment with GPD in a new aircraft program by co-developing a complete aircraft section jointly with a key offshore supplier.

The challenges that arose from that first experience proved to be valuable learnings for the company. While Cessna used the supplier’s engineers to carry out part of the design work, but required that Cessna processes and standards be followed. The tension between Cessna’s involvement and the supplier’s desire for independence proved to be a source of friction and eventually Cessna opted for a second source for producing this section. The company realized that in the future it might be more prudent to outline product performance specifications and grant more decision-making authority to the supplier on structural design, manufacturing standards and processes. Despite the tensions that arose between the company and the supplier, many Cessna executives understood that significant learning took place on both sides and indicated that they would work with the same supplier again.

Second GPD Stage (Textron’s Global Technology Center): Cessna’s second GPD effort was in direct response to impressive growth expectations. After suffering a significant downturn during 2001-03, the cyclical business jet industry bounced back; Cessna was expecting the business segments in which they operated to grow by more than 100% between 2004 and 2009. Recognizing the tremendous growth opportunity, Cessna performed an internal assessment of their design, development, manufacturing capabilities, and their ability to capitalize on growth expectations. Given the short lead time available to meet the incremental requirements and cost factors involved, Cessna concluded that the growth opportunities could only be met through outsourced design and development (not just build-to-print). Product ar-
architecture development and system integration, however, would remain in-house to ensure that the brand DNA was not compromised.

In 2004, Cessna’s parent company, Textron, established the Global Technology Center (GTC), a corporate sponsored engineering resource center located in Bangalore, India, as an effort to provide lower cost and capable engineering capacity to group companies. Within two years, Cessna hired and trained engineers in various technical specialties. In addition, the company identified available capability in certain aircraft development activities with a second Indian vendor.

In 2006, Cessna was operating under a small scale GPD model wherein a supplier’s employees, co-located at the GTC, worked on tasks that matched their capabilities. Concurrently, Cessna was developing Cessna-dedicated GTC employees on specialized jobs with an aim of achieving system/sub-system design and development capability within a few years.

**The System Architecture-Based DSM:** The high-level architecture-based DSM, based on inputs from Cessna’s system architecture group, indicates that modular decomposition for Cessna’s jet aircraft is not possible. Developing the DSM was challenging, as the architecture could be defined either by functional systems like electricals, hydraulics, pneumatics, etc. or by sections like cockpit, cabin, etc. (see Fig. 2-14). The functional systems are distributed throughout the aircraft, touching almost all sections. Similarly, each section contains elements of most of the functional systems. For example, the electrical system starts at the cockpit, and runs through the cabin, the tailcone, the wings, and the engine.

![Figure 2-14: Typical Aircraft Sections](image-url)
The section-based DSM developed provides key insights about the interdependencies/interactions between major aircraft sections and functional systems. The aircraft can be divided into six different 'section-based' systems - cockpit, cabin, tailcone, wings, empennage, and engine package (Fig. 2-14). Each section comprises of structural sub-systems/components that are unique to that section, eg. shell and structure in the cockpit, and functional systems.

The DSM developed (Fig. 2-15) considers, for each section, those functional systems that have a significant role, e.g. flight controls in cockpit, wings and empennage, fuel systems in wings and engine package, etc. The system architecture integrates all of them. At the overall system level, the product requirements are developed through sharing information with structural/functional systems like structure, avionics, electrical system, etc. These product level requirements for the structure/functional systems, are in turn, developed through information exchange with the respective functions in the sections (the information from and to the functional systems of system architecture in the DSM). As is evident from the DSM, most interactions are contained within sections, though some interactions/information dependencies occur between sections. Such interactions/ information dependencies will need to be managed if the teams developing the respective sections are not co-located.

Figure 2-15: Cessna: System Architecture based DSM
2.3. **GPD CASE STUDIES**

**Key Takeaways:** While Cessna is going forward with expanding the development work content at the GTC, it is expected that in future a lot of their offshore development work will be done through outsourcing (either the non-specialized jobs with the supplier's employees at the GTC or through system/sub-system development with offshore suppliers). The following takeaways outline the issues that Cessna needs to be careful about as they offshore to suppliers.

**Co-Location:** Clearly, as Cessna considers moving from its current vertically integrated development structure to one with more supplier involvement, suppliers providing design capabilities will play a key role. The strong dependencies of each of the systems/sub-systems on the product architecture (as evidenced from the DSM) clearly point towards co-location of the providers with Cessna engineers, at least in the early part of the program when the package and specifications are developed. Subsequent co-location would depend on the level of interaction required. The DSM would need to be expanded to identify the relevant interactions that would require co-location.

**Systems Interactions:** The DSM shows interactions between functional sub-systems - electrical, flight controls, pneumatics, etc.; however, the exact nature and details of these interactions need to be studied further. Such a study will help determine the need for Cessna personnel involvement (and the number of people needed) if the systems are provided by different suppliers. A clear roles and responsibilities (R&R) may need to be developed in that case.

**Culture:** Cessna follows the standard Textron 7-stage New Products and Services Introduction (NPSI) process. If Cessna moves to a more horizontal structure (more outsourced design and development), the stage timings and applicable processes may need to be modified(updated to reflect the upstream involvement of suppliers providing design capabilities and aircraft industry standards, as most of these suppliers operate in the wider aviation industry, and may resist adopting 'Cessna-specific' practices. Similarly, Cessna engineers will be challenged with learning to work with outsourced suppliers whose practices may not mirror those followed at Cessna.

**Definitions:** Cessna would likely face a dilemma in defining systems/sub-systems for suppliers to design, due to the high level of interactions presented in the DSM. Though the systems in this DSM have been defined in terms of 'sectional' systems, it is also possible to develop a DSM based purely on functional lines, e.g., electrical, pneumatics, etc, and in line with the sourcing strategy being considered, e.g., a single supplier who provides all the electrical wirings versus a wing supplier who is responsible for all the electricals within his scope of supply.

### 2.3.5 Honeywell-Aerospace Division: Task Based Offshoring

Honeywell International Inc. is a $31 billion diversified company headquartered in Morristown, New Jersey. Honeywell's products span four key areas: aerospace (engines, avionics, aircraft components), automation and control solutions(safety systems
for homes, buildings, industrial sites, airports), specialty materials (chemicals, fluorocarbons, advanced fibers), and transportation systems (automotive turbo systems, friction materials).

Phoenix-based Honeywell Aerospace (formerly Allied Signal), a $9 billion division of Honeywell, is a leading industry supplier of avionics and electronics, consumable hardware, engine controls, environment controls, landing systems, power systems, and propulsion engines to the defense, space and airline industries. The division has design and development centers located at several U.S. product sites. This case study focuses on Honeywell Aerospace’s avionics operations (Chang (2007)).

Honeywell follows a seven-stage gate product development process. These stages are followed for new product introduction and cost reduction activities on existing products (also known as value engineering activities). The complexity of the products that Honeywell Aerospace manufactures warrants a strong level of interaction and collaboration between design, marketing, planning, and an integrated supply chain to meet program cost, quality, and timing objectives. A growing competitive landscape has led to increased cost pressures, more challenging schedule requirements, and rising manufacturing and quality expectations.

**GPD Dilemma:** The Advanced Manufacturing Engineering (AME) group was created within the Aerospace Integrated Supply Chain in 2005. Its charter is to drive down program costs by enhancing collaboration between different participants of the product development process.

As AME grows, it will face local hiring constraints (due to cost) and, per the mandate of Honeywell’s CEO, the group will have to look to hire internationally, particularly in low-cost regions. Labor costs, efficiency and co-ordination efforts will all be considered with any decision AME makes regarding off-shoring. The AME group was considering three location options for Honeywell Aerospace’s design and development activities: Local: current site, close to/near other departments that they need to collaborate with, e.g., Phoenix, New Jersey Medium Cost: close to current location, close time-zones, allowing certain customer-constrained jobs to be moved there; lower labor costs than local, e.g., Puerto Rico, rural United states Low Cost: distant location with cheapest labor costs, e.g., India, China

Any location option that AME chooses would involve various costs like: a) Labor costs related to manpower (time in hours). b) Co-ordination and collaboration costs related to the time spent carrying out tasks which involve information sharing/transfer. c) Fixed costs related to setting up new facilities, hiring and training, etc.

There are likely to be constraints of the type: a) Potential capacity (manpower) at off-shore locations. b) AME tasks that are required to be executed locally. c) AME tasks that need to be co-located with other tasks (including non-AME tasks).

**Decision-Making Approach:** Each option that the AME group contemplated had
2.3. GPD CASE STUDIES

associated risks. For example, while resulting in lower labor costs, it was evident that moving tasks from local operations to medium cost or low cost locations would require more co-ordination and collaboration time and, therefore, add costs. Honeywell had to ensure that an appropriate trade-off, such as lower labor costs against higher co-ordination and collaboration costs, was achieved prior to off-shoring certain tasks. The AME group went through the following steps to determine the tasks that could be off-shored.

**Step 1:** A full list of tasks that AME is responsible for carrying out was generated. Tasks that had to remain on-shore were identified while groups of tasks that needed to be co-located were bundled as single tasks.

**Step 2:** A (numerical) design structure matrix (DSM) was built (Fig. 2-16). As shown, there are nine sections in the DSM. Each section represents a combination based on the relative locations of a pair of tasks (local, medium cost country, low cost country). One of these sections has been expanded in Fig. 2-17. The rows (and columns) list each of the AME tasks that could be off-shored and each of the other departments that AME interacts with (design, integrated supply chain, and marketing and program management - these departments are constrained to be local).

![Figure 2-16: Honeywell: Task-Based DSM (Structure)](image)

**Step 3:** For each task under consideration, the estimated labor time per task for all aerospace programs was expressed in hours per month. The DSM captured the approximate hours of interaction between various tasks (co-ordination time in hours per month). *Fig. 2-17* is a sample drawn from the DSM. The co-ordination time between task *Should-Cost Modeling* and Engineering is 60 hours when this task is done locally (shown as A in *Fig.2-18*). Similarly, the coordination time between tasks *Should-Cost Modeling* and *Quote Acquisition* is 10 hours when both the tasks are done locally (shown by B in *Fig.2-18*), but increases to 15 hours when *Quote Acquisition* is done in a medium cost country (shown by C in *Fig.2-18*). These coordination times obtained from the DSM were used to derive the coordination costs.

**Step 4:** For each potential location, the hourly (relative) labor costs and relative efficiencies for carrying out each task were identified. These helped determine the labor and coordination costs used in the model (using the coordination time from the DSM).
Step 5: An optimization problem was developed to identify the locations for various tasks.

Key Decisions: Subsequent to the above steps, Honeywell was able to identify tasks that could be off-shored to a medium and a low cost location. The medium cost location was chosen on account of its skilled workforce and the ease of coordinating work with the tasks based in the United States. The tasks were grouped together and job descriptions then developed, based on skill requirements and the task interactions (defined from the DSM).

2.4 Summarizing the Case Studies

As outlined earlier, we analyzed the GPD efforts of the five firms (section 2.3) from the why, how, and what were the results perspectives. In this section we first classify the reasons for firms to pursue GPD and then summarize the 'how' aspect from two perspectives: the organization approach and the architecture decomposition approach.
2.4. **SUMMARIZING THE CASE STUDIES**

2.4.1 Why do firms do GPD?

Ghemawat (2007) stated that an organization's globalization is a mix, in varying proportions, of adaptation (meeting global market needs), aggregation (of regional efforts) and arbitrage (attaining efficiencies). For design and development activities, adaptation and aggregation can be considered as home-base exploiting and arbitrage as home-based augmenting (Kuemmerle (1997)). We follow on similar lines and classify the reasons why firms pursue GPD along two motivations: market needs (our case studies did not have any evidence of this) and efficiencies.

Firms may need to make changes in their CES as they explore overseas markets. The specific market needs may be designed and developed in the related market. In such cases, some system architecture development and/or system integration efforts may also be done at the GPD site. Firms may also pursue GPD seeking efficiencies: seeking competence through specialized knowledge available at offshore locations, cost reduction opportunities through lower manpower cost structures, and creating an option for hedging design and development capacity. In many cases, firms may opt for GPD to meet market needs while utilizing efficiency benefits. Each firm in our study was seeking efficiencies in their respective GPD effort.

We observed organization forms motivated by various efficiency considerations in our case studies (Fig. 2-19). While cost savings were the prime consideration (Danaher Motion, Intel, Cessna, Honeywell), these firms had also organized themselves for other opportunities. Danaher Motion and Cessna were looking for hedging opportunities too, albeit in different ways. Whilst Danaher Motion used a flexible design workforce between group companies, Cessna had a combination of inhouse/outsourced design workforce to meet the PD work content fluctuations. On the other hand, Intel’s GPD efforts, in addition to cost savings, included competence seeking as they setup competence centers globally. Pitney Bowes’ GPD arrangement with Canon was
based on dependence for superior printer technology development.

![Diagram of GPD Considerations]

**Figure 2-19: GPD Considerations**

### 2.4.2 Organization forms

We analyze the firms' approach towards GPD (Fig. 2-20) through the 2x2 make-buy in-out matrix (Fig. 1-2). While two firms (Intel and Honeywell) set up captive offshore development centers, two others (Danaher and Pitney Bowes) sought supplier support for their offshore engineering activities, and Textron (Cessna) setup an engineering center with a mix of own and supplier staff. Though both Honeywell and Danaher identified content that could not be offshored, their respective offshoring approaches were different (inhouse and supplier respectively). Intel and Honeywell needed to have captive offshore units because the tasks offshored by them were firm-specific. Though these tasks could utilize the existing talent and knowledge available in the GPD locations, subsequent firm-specific knowledge was required. Similarly, Textron (Cessna) identified mission-critical tasks which remained inhouse at their offshore location but like Danaher Motion, they also had other tasks which were more 'general' engineering and development oriented and hence it was possible to identify outsourcing options for these offshoring content. Pitney Bowes sought to offshore competence for a core part of its product with an offshore supplier. This approach was clearly a case of competence seeking through outsourcing, and offshoring happened merely due to the location of the supplier.

### 2.4.3 Architecture decompositions

The respective decomposition approaches followed by the five firms, towards GPD, were:

- Danaher Motion: product & process decomposition
- Pitney Bowes: product decomposition
2.4. SUMMARIZING THE CASE STUDIES

In addition to the architecture decomposition followed, we also assessed the types of interfaces after system development (Fig. 2-21). Following Fujimoto (2002), we differentiated the types of interfaces as open or closed. Closed interfaces are specific to the product or the firm, while open interfaces are common/standard across firms in the industry in which the firm operates. Thus, with open interfaces, there exist opportunities to seek offshore suppliers’ existing designs, while closed interfaces require the offshore location to design interfaces that are specific to the firm. Open interfaces also reduce the coordination requirement during development, thus reducing the need for the firm to track the supplier closely (Sanchez and Mahoney (1996): supplier-manufacturer relationship).

In an integral architecture, it is difficult to identify open interfaces within and Honeywell presented an example of this wherein decomposition still identified requirements for coordination. Intel, Cessna and Pitney Bowes were more ‘modular’ in design with identified closed interfaces. Even Pitney Bowes, with clear defined interfaces between the modules, had closed interfaces which were specific to their product. The open interfaces in the products/systems of these firms existed in the form of electrical connectors, but that level of design existed within the scope of the design and development offshore rather than at the scope. Only Danaher Motion had certain open interfaces that were being explored for subsequent offshoring (control systems) to utilize the existing competencies available with the offshore supplier.

- Intel: process decomposition
- Cessna: product (section & function) decomposition
- Honeywell: process (task) decomposition

![Figure 2-20: GPD Approaches](image-url)

Figure 2-20: GPD Approaches
CHAPTER 2. A SYSTEM ARCHITECTURE ANALYSIS OF GPD

Product/Process Architecture

<table>
<thead>
<tr>
<th>Integral</th>
<th>Modular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeywell</td>
<td>Cessna</td>
</tr>
<tr>
<td>Pitney Bowes</td>
<td>Danaher Motion</td>
</tr>
</tbody>
</table>

Figure 2-21: Architecture Assessment and Type of Interface

We summarize our observations from the five case studies in Fig. 2-22, considering two factors at a time. The figures in the top row illustrate that a firm may outsource the GPD activities when seeking efficiencies, whether for cost savings or hedging benefits. Similarly, as shown by the case of Pitney Bowes, firms may seek offshore suppliers for competence but these should be considered as ‘outsourcing for knowledge’ (Fine and Whitney (1996)) rather than as offshoring opportunities. We also observe that the GPD content that is outsourced is determined by product decomposition, either on its own or after process decomposition. Similarly the figure in the second row in Fig. 2-22 shows that the architecture decomposition is generally hybrid (product after process or process after product) unless the GPD motive is purely competence seeking or cost savings. We derive some implications for GPD based on these observations in the next section.

2.5 Key Learnings from Case Studies

2.5.1 Ownership Implications for GPD

We collate our observations from section 2.4 in Fig. 2-23 and analyze the figure to arrive at some ownership implications for GPD:

1. In the case of Pitney Bowes, they could not have proceeded on their product without Canon support. We term this quest as seeking complementary knowledge and believe that such a case needs to be treated as one of ‘outsourcing for knowledge’ (Fine and Whitney (1996)) rather than offshoring, the offshore
2.5. KEY LEARNINGS FROM CASE STUDIES

location of the source of knowledge being a happenstance. However, a firm may set up an offshore engineering center to benefit from the talent available at the offshore location; we term this as seeking incremental knowledge. An example of this would be Intel which set up development centers at Russia and India to take advantage of local expertise.

2. A firm pursuing GPD for cost savings will set up its own engineering development center if the tasks to be offshored relate to core competence or are ‘mission-critical’ (Cessna) or such that specific product-related development talent (specialized) is required to be developed with the engineering resources available at the GPD location (Intel and Honeywell). All other tasks identified for offshoring can be outsourced. We observed that the outsourced content generally tends to be of ‘general’ or ‘commodity’ nature (with respect to engineering development competence available at GPD location) as seen in the cases of Danaher Motion and Cessna. Availability and identification of open interfaces (Fujimoto (2002)) can help get benefits of utilizing existing designs/capabilities with the GPD supplier.
3. When tasks are offshored for capacity hedging benefits, the 'extra' or 'spare' capacity could be inhouse or outsourced. Though Cessna and Danaher Motion had opted for outsourced engineering centers to hedge design capacity, there do exist cases (Schneider Electric in PTC (2005)) when a firm may seek to establish a captive engineering center. When a supplier is used for design and development capacity hedging, managing the relationship with the supplier becomes important as the supplier needs to provide the relevant design workforce when required.

![Figure 2-23: GPD Ownership by GPD Consideration](image)

**2.5.2 Implications for Architecture Decomposition for GPD**

We also derive some implications for architecture decomposition (Fig. 2-24):

1. Decomposition helps in identifying offshoring content. Opting for process and/or product decomposition depends on the firm’s GPD motive (cost savings, competence, hedging opportunity).

2. When a firm is seeking GPD for cost savings or for capacity hedging considerations, it may proceed by offshoring certain tasks. So the firm needs a process decomposition exercise to identify appropriate tasks. However, often, the entire task responsibility may not be offshored together, rather it may be offshored in stages. An additional decomposition (thus now requiring a hybrid DSM) is then needed. Amongst our cases, Danaher Motion followed a process-product...
2.5. KEY LEARNINGS FROM CASE STUDIES

decomposition, Intel a process-product-process decomposition, and Cessna had identified the tasks and then had a product-function decomposition to identify the exact offshoring content.

3. A firm pursuing GPD for complementary knowledge needs to follow product decomposition, e.g. Pitney Bowes for outsourcing the printer technology development. Such decomposition helps in identifying the exact development responsibility that is offshored/outsourced. However when the firm seeks incremental knowledge (Intel looking to tap on design talent available offshore), it needs to follow a product-process hybrid DSM to help identify the exact offshore content (and interface needs) as the primary knowledge exists within the firm and an identified content is being sought from the offshore location.

![Architecture Decomposition by GPD Consideration](image)

Figure 2-24: Architecture Decomposition by GPD Consideration

2.5.3 Learning to do GPD

We observed the interesting experiences of Danaher Motion and Cessna. These firms were not quite successful with their initial offshoring experiences. Danaher Motion’s initial offshoring experience consisted of an ‘over the wall’ approach wherein a set of tasks were passed on to an offshore supplier and after slow responses, were brought back onshore (insourced). In their next offshoring attempt, they transferred the same content but after two additional steps: joining their corporate effort and after substantial training of their new offshore supplier. In Cessna’s case, it was their first experience of offshoring the system development of a module to a supplier. They faced challenges in the development effort. However, they believed that it was a learning experience for them and they would not hesitate to use the same offshore supplier again.

The above examples illustrate that offshoring is a process that a firm needs to learn about. Besides the time zone, geographical and cultural challenges that the
firm faces, the firm also needs to understand the work 'standard' in terms of product knowledge, standards followed, existing processes and practices, etc. at the offshore location. A firm may try to force their standards and processes on their suppliers, but then they are likely to face initial resistance and hence loss of efficiency (expensive). It may not be easy to change the prevalent practices immediately, even in an inhouse development facility. The benefits from offshoring design and development activities is unlikely to be immediate and requires patience on part of the firm.

2.6 Direction for Future Research and Conclusion

We started this paper with a review of the academic literature on GPD and system architecture. We then analyzed, using system architecture principles, the GPD efforts of five firms engaged in the design and development of complex engineered products. We identified the similarities in their GPD approaches from need, architecture and organization viewpoints. This helped us to identify implications (ownership and architecture) for firms intending to pursue GPD. Through these implications and observations from the case studies, we were able to develop a process for GPD. Amongst the various inferences and future potential research directions that emerge from the case studies, the key could be those that address why the firms are doing GPD, how they are doing GPD and the rationale for the same, and what are the key challenges that they face in GPD and the corresponding decisions that they take.

As outlined earlier, the case studies have shown that the mode of sourcing (make/buy) and location for sourcing (onshore/offshore) are parallel decisions. It is important for a firm to identify its core competence and intellectual properties, and which of those they would be willing to share. In CES, core competence or intellectual property is primarily a sub-system or a component of the final product, and rarely the complete CES. Literature (Novak and Eppinger (2001)) has shown that there exists strong complementarity between complexity in product design and vertical integration of production, with in-house production being more attractive when product complexity is high. This drives an idea for research along the lines - using system architecture tools, how easy or difficult is it to decompose a CES so that GPD of sub-systems/components can be pursued? What is the relationship between design complexity and design integration (vertical and horizontal)? Further, from the information processing view that architectural knowledge tends to become embedded in the structure and information processing procedures of established organizations (Henderson and Clark (1990)), it may be worthwhile to see if GPD opportunities (either pursued due to adaptation or arbitrage reasons) drive architectural changes and if they do, how does that impact the firm?

Even for a firm that is able to identify its core competence and intellectual property that it would want to retain in house, it may still be very difficult to offshore/outsourse the remaining due to the information flows, linkages, dependencies, etc.
2.6. DIRECTION FOR FUTURE RESEARCH AND CONCLUSION

present between the identified in-house and outsource processes/sub-systems/parts. This challenge is magnified for CES. Managers face a significant problem in identifying the GPD content. We believe that managers need to first recognize the difference between offshoring and outsourcing. The trade-offs are different between these cases. Further, most academic and practice literature calls for offshoring of modular designs/activities. These are quite difficult to identify, particularly in CES. Managers need to be aware that modularity in manufacturing need not necessarily mean modularity in design. CES are designed and developed by large teams of engineers who need to frequently share and exchange information, and it is challenging to identify engineering tasks that are truely modular (Pitney Bowes could do so).

System architecture can play a very useful role here. Clearly the outsourced package is invariably less than the identified ‘outsource-able’ package (after make-buy analysis). Similarly, the entire ‘offshore-able’ package may not get offshored. This may not be the most desirable situation, more so when a firm is firm is pursuing GPD for efficiencies through cost savings. Here system architecture tools like DSM can play an important role. In this paper, we have shown how DSM could be used to analyze GPD actions. Research opportunities exist to explore and identify measures or constructs to quantify the dependencies between the processes/tasks or sub-systems/components. Such a quantitative approach can help prioritize and optimize GPD efforts for maximum benefits (e.g. Intel and Honeywell cases). These constructs and measures need to first identify the system architecture approach that the firm needs to follow - process decomposition, or task decomposition, or product decomposition (functional or sectional), etc. The construct and measures identified should correspond to the decomposition route chosen.

The key performance measurement constructs for product development are cost, timing, and quality. The five firms that we studied, pursued GPD for efficiency reasons in different ways (Fig. 2-19). Tools and methods are needed for measuring the respective efficiency gains from GPD. Such methods need to carefully consider the trade-offs involved. The Honeywell case is a good starting example, where the lower labor cost of medium cost and low cost offshore locations is offset by increased coordination requirements. A mixed-integer programming formulation can be used to determine the locations for the respective tasks, optimizing the trade-off between the reductions in labor costs and the increase in coordination costs for moving away from on-shore activities.

\[
\text{Min } \sum_{i} \sum_{k} X_{ik}(C_{ik} + W_{ik}) \quad i : \text{task}, \quad k : \text{location}
\]

subject to constraints

\(X_{ik}\) is an indicator (decision) variable, with value 1 when task \(i\) is done at location \(k\). \(W_{ik}\) is the manpower cost associated with the individual engineering effort for doing task \(i\) at location \(k\) and \(C_{ik}\) is the manpower cost for all the coordination that
needs to be done for task $i$ at location $k$. Thus, $C_{ik} = \sum_{i'} \sum_{k'} C_{i'k'k}$. The prevailing constraints also need to be incorporated. This is a very primary formulation, and research can lead to more sophisticated models that incorporate information flow, dependencies, feedback loops, etc. from system architecture decompositions, thus helping to identify better efficiency opportunities in GPD. In the next chapter we develop the theory leading to a recursive equation for offshoring decisions and apply it in an industrial setting. We use economic modeling to first optimize the global product development organization of a firm and then identify some key factors that impact offshoring and their respective effects on the offshoring decision. Managers need to embrace economic modeling towards GPD content identification.

Earlier in the chapter (section 2.1) we discussed the challenges in communication and knowledge transfer that global R&D organizations face. Product development is the transformation of embedded knowledge to embodied knowledge (Madhavan and Grover (1998)). GPD brings with it the requirements of teams dispersed globally to be able to communicate and comprehend each other. There is added complexity that the teams could be operating in time zones that do not overlap during working hours. Product development requires constant and consistent communication. As observed in the Honeywell case, the coordination time required between tasks increases when the tasks are done from different locations. Most decompositions stretch to use numerical DSMs to provide a quantification to the level of coordination required, but we have not come across any model that incorporates the cultural differences (and actions required to overcome), communication challenges, or time zone differences, and has tried to incorporate them into a decision framework. Sosa et al. (2004) studied the mapping of design interfaces in the product architecture to the communication patterns within the development organization in a firm, and found that strong design interfaces tend to be more likely to be aligned with team interactions. An interesting study could be to observe the change in alignment with GPD - do teams in different locations (with their cultural, communication, time zone challenges) continue to have the same level of interactions or if they change, how do they change, given that their design interfaces remain the same. If they change, is it possible to quantify the change, identify the causes for change, and possibly establish a model to predict the change based on these causes? This study may need to extend across firms.

The above aspects of GPD lead us to consider a key deliverable of any product development process - timing. Most firms involved in CES tend to follow a stage gate process (Cooper (1993)). Assuming that the product definition has been completed, a detailed time plan to launch is then laid out. Such a plan does take into account the resource availability. In GPD, these resources may be available, with the added variability of different location, culture, communication methods, and time zone differences. This can lead to research studying the changes in project time with GPD. The research could look at the impact of GPD on project timing from different perspectives: Does project timing change? If so, by how much? Do firms accept this change in timing or do they, in the event that they are using a location with
significantly lower labor costs, hire more personnel to maintain or expedite timing? How does the capability of engineers hired in the GPD location compare with the home base (a measurement construct may need to be developed) and how does that impact project timing? Does a firm incorporate learning and hence expect product development time for the sub-processes/sub-systems offshored to reduce? How are these learnings identified and incorporated in the offshoring decision? How does GPD influence the firm’s ability to respond to market changes (leading to changes in product definition)?

In addition to cost and time, the other major PD parameter is quality. Though a firm may pursue GPD for arbitrage, it is unlikely that they may compromise on the quality of the PD process. We observed that Danaher Motion/Dover faced performance problems in their initial GPD effort and had to change their respective offshore suppliers. Similarly, Cessna was not satisfied with the initial progress in their first GPD efforts, though in retrospect they would be willing to work with the same supplier again. Quality dissatisfaction in GPD could arise due to inability of GPD locations to meet home base requirements in terms cost, specifications, timing, etc., communication issues leading to misinterpretation, cultural differences, etc. Considering that GPD efforts are mushrooming now, there are opportunities to research the determinants of good quality in GPD and perhaps help arrive at proper quality parameters which can be used during GPD assessment.

Most of the research ideas above perhaps allude to a single GPD action by the firm. In reality, a firm is likely to start slow, outsource a part of a process or a sub-system, assess the performance, and then decide on how to proceed. It is likely to be a time-phased sequential decision process. In Phase 3 of the Danaher Motion/Dover case, we have tried to outline the possibilities for better utilization of the GDC - the final decision to do so would depend on Dover’s satisfaction of the performance of the GDC in Phase 2 and the benefits that the GDC will provide in Phase 3. Similarly, Pitney Bowes, through product decomposition, has been able to outsource the manufacturing of modules. These suppliers may have the capability to progress on to designing the modules thereafter (Canon is already designing the printer technology and the finishing module is a natural step forward for them). Similarly, Cessna will look for higher utilization, through a mix of in-house/outsource, from the GTC. By developing a suitable real option structure (Dixit and Pindyck (1994), Trigeorgis (1996)), researchers can look at how system architecture can progressively identify sub-processes/tasks or sub-systems/components for outsourcing or offshoring. By going in for a sequential approach to GPD, the firm will be able to evaluate the progress until date and the prevailing environment before deciding on the quantum of task/component for the next stage of GPD.

GPD is emerging as the valuable tool for managers. While the first wave of GPD is likely to be a result of arbitrage or adaptation considerations, soon aggregation on regional basis may take over. Though earlier literature has covered multi-national R&D, they have focused more on research. Simultaneous development as envisaged in
GPD has received scant attention in literature until Eppinger and Chitkara (2007) and Anderson et al. (2008). In this chapter we outlined some of the relevant literature on R&D networks, presented five case studies of GPD experiences of companies engaged in complex engineered products, and built on the same to identify a process for GPD that firms can follow. Our findings and proposals reflect the current state of GPD practice and related opportunities therein. We expect that as GPD practice evolves, our findings and proposals will modify accordingly.
Chapter 3

Optimal Structuring of Global Product Development Organizations

Chapter Abstract: This chapter proposes a methodology to optimally structure the global work distribution for a product development (PD) organization. Research in optimal work distribution/allocation in PD organizations has been limited, so far, to prescriptions recommending distribution of modular tasks/responsibilities. However, most PD efforts are characterized by significant complexity in information sharing and information dependency between PD tasks which are performed in parallel. This complexity is represented by coupling in the system architecture (product, process, organization) of the firm. Further, such complexity restricts the PD performance of the firm when the participants of the PD organization are globally distributed (GPD). We build on our earlier field studies and existing literature to identify the key factor that contributes to the performance of the GPD organization: coordination required between PD tasks. We incorporate this factor to develop a recursive equation model that structures the global work distribution of a PD organization. We apply our model to optimally structure the GPD organization in an industrial setting, utilizing the design structure matrix (DSM) to identify the system architecture of the firm. Our optimization results, based on detailed modeling of coordination costs, show significant cost savings through a re-structured PD organization. Subsequent analysis of our results shows that while offshoring based on modularity is generally right, it is not the whole answer as there exists a trade-off between the efficiency of performing specific PD tasks at the offshore location and the modularity of the task.

In the previous chapter we observed the GPD efforts of five firms involved in the development of large complex engineered products. We analyzed their respective approaches from a system architecture view using the DSM tool. We then summarized the findings by proposing a GPD approach that a firm may follow. We recognized that while our summary reflected our observations in these firms, developing "thumb
rules’ to enable firms (engaged in the design and development of complex engineered products) is a rather daunting task. Most of the firms’ selection of GPD content evolved from a ‘gut feel’ or ‘thought it was easy’ (to get the offshore work done) approach. There appeared to be a lack of coherence amongst the set of components or product development activities that were offshored. To understand the way in which a firm needs to develop its GPD organization, we frame our research question as: How does a firm optimally structure the global work distribution, over time, of its product development organization? Further, given our interest in complex products, the role of system architecture in the analysis of complex products, and our observation of the relationship of system architecture and GPD content, we extend our research question to: How does the firm’s architecture affect these work distribution decisions?

We explore the above research questions in this chapter. In the previous chapter we had completed a literature survey on GPD and system architecture. In this chapter we discuss complex products/systems and their relevance to the offshoring questions (outlined in the previous paragraph). We then proceed to develop a theory, incorporating the firm’s architecture, towards structuring an GPD organization by building on existing research in the areas of operations management, product development, organizations, and transactions theory. Finally we apply this model in an industrial setting to show how a firm can optimally structure the global work distribution of its product development organization.

3. 1 Introduction

3.1.1 What is Global Product Development?

Product development (PD) has been defined and studied in many ways. Brown and Eisenhardt (1995) segregated the research on PD along three streams: PD as a rational plan (careful planning followed by meticulous execution supported by top management), PD as a communication web (communication within and with outside suppliers stimulates the performance of development teams) and PD as disciplined problem solving (overall balanced act across all activities leading to project success). Other definitions of PD include those by Wheelwright and Clark (1992) (effective organization and management to enable an organization to bring successful products to market, with short development times and low development costs), Krishnan and Ulrich (2001) (transformation of a market opportunity into a product available for sale), Ulrich and Eppinger (2004) (set of activities transforming the market opportunity to the production, sales and delivery of a product), Ulrich and Ellison (2005) (information processing), etc. In yet another definition, Madhavan and Grover (1998) defined new product development as the process that converts embedded knowledge (knowledge residing either inside or outside the organization) to embodied knowledge (knowledge incorporated into the product). Loch and Kavadias (2008) summarized
3.1. INTRODUCTION

various definitions of PD and characterized PD as comprising of four key elements: variant generation process, selection process, transformation process, and coordination process.

GPD, specifically, has been defined by Eppinger and Chitkara (2007) as combining certain centralized functions with some engineering and related PD functions distributed to other sites or regions of the world - the practice may involve outsourced engineering work along with captive offshore engineering facilities. Along similar lines, Anderson et al. (2008) refer to distributed product development as the use of organizational arrangements involving multiple organizations that are separated by firm, geographical, or other boundaries, that are used for product development.

From the above definitions, we observe that GPD is an organization form for a firm's PD activities. A firm may resort to this organization form to address specific elements amongst those outlined by Loch and Kavadias (2008). This organization form is dynamic and seeks to generate increasing value, over time, for the firm.

As discussed in the previous chapter, a firm's GPD efforts are a mix of adaptation, aggregation, efficiency seeking (through cost reductions, or seeking competencies) and capacity hedging. In this chapter we model for a firm that is pursuing GPD for cost reduction (through re-assignment of work content within the firm, across locations). Subsequently we discuss the flexibility of our model towards the other GPD considerations.

3.1.2 What are Complex Products/Systems?

While academic literature has extensively covered modular products/systems (Ulrich (1995)), it is very difficult to identify most products or systems as modular. Rather most of them can be called complex systems. Complex products are made up of a large number of parts that interact in such non-simple ways that it is not easy to infer the properties of the product from those of the parts and their given interactions (Simon (1969)). Our interest lies in those complex products that are engineered, i.e. CES, which has been discussed in section 2.1.2. Such CES products have a significant number of interaction needs between the systems, sub-systems, components, tasks, or activities that they are made of (Fig 2-2). These interactions necessitate significant coordination needs to ensure that appropriate information exchange takes place (Clark and Fujimoto (1991), Wheelwright and Clark (1992)).

As outlined in section 2.2, it is rare for a firm engaged in the design and development of CES to offshore the complete set of activities other than when either it is to an offshore captive unit or the product is being supplied by an ODM. At times the design and development may be offshore (with outsourcing) to design houses but these become rare as the complexity of products increases. However when a firm is in the process of setting up an offshore development center (captive or supplier), it starts with a set of tasks, with the expectation that this set would grow over time. Identification of these set of tasks is challenging for complex systems due to the coordination
needs.

As shown earlier (Fig 2-3), CES can be thought of being made up of sub-systems which, in turn, are made of components or tasks (referred to as ‘task’ hereafter). At the task level, there can be a need for significant coordination during offshoring. As shown in Fig 2-3, offshoring of a task that has coordination needs with another task that is at a different (home) location is hard compared to offshoring of either a task that does not have such coordination needs or a set of tasks that have coordination needs within themselves. However in some cases the firm may decide to go in for offshoring the component with coordination needs across locations when it may be seeking product competence and is unable to identify the necessary interfaces (Fujimoto (2002)) to eliminate coordination needs. Generally these happen with outsourcing where the supplier with the necessary competence happens to be offshore (a happenstance). In chapter 2 we saw the example of Pitney Bowes who could identify the interface needs to ensure outsourcing to an offshore supplier Canon with limited coordination needs during component development. It could also arise when a firm offshores a task because it believes that the benefits may outweigh the challenges posed by coordination between locations.

The above offshoring approaches can be classified into two types for CES: component offshoring and sub-system offshoring (Fig 2-4). Each of these GPD organizational arrangements has its own benefits and challenges. While sub-system offshoring may ensure that coordination needs are controlled within a location, it could lead to loss of sub-system development capability at the home location. Similarly component development offshoring will require significant coordination across locations and a potential loss of efficiency.

3.2 Theory and Model Development

Since GPD is a relatively new research topic, there is limited academic literature, in particular economic modeling, that identifies the approach that a firm should take with respect to offshoring content. At the base of any economic modeling is the trade-off question which is determined by the intent of the exercise. As outlined in chapter 2, firms pursue offshoring for cost savings, capacity hedging, competence seeking, adaptation and aggregation purposes. Here we will develop the theory and model that reflect the evolving GPD organization for a firm seeking cost savings. We use existing theories in product development, operations management, organizations, and organization economics literature to build our model. Since a lot of this literature was developed for outsourcing (make/buy decision), we will first distinguish between offshoring and outsourcing.

As discussed in chapter 1, offshoring involves the location of the various individuals and groups involved in the PD activities. The challenges here pertain to those of ensuring appropriate exchange of information or coordination across time-
zones, cultures, geographic distances, etc. (Anderson et al. (2008), Boh et al. (2007), Loch and Terwiesch (2008), Srikanth and Puranam (2008a), Srikanth and Puranam (2008b)). Thus, activities that require significant coordination during product development stay onshore whilst others can be offshore.

On the other hand, outsourcing involves the ownership of the various resources involved in the PD activities. The make/buy decision is driven by various factors, including cost and competence. The key challenge here is to protect those resources of the firm that are strategic in value and provide sustained competence. In a CES, as seen in chapter 2, system development and system integration is rarely outsourced (except for ODMs). The outsourced PD activities are defined during system development and generally constitute a subset of PD activities. It is rare for a PD activity that is considered strategic to be outsourced unless the firm believes that the value proposition (Fine (1998), Fine et al. (2002)) from such an action will be sustainable (avoid ‘outsourcing trap’ (Anderson and Parker (2004)), e.g. Pitney Bowes outsourcing printer development to Canon in chapter 2.

We plot the respective trade-offs of outsourcing and offshoring along different axes in Fig. 1-2 (Ulrich and Ellison (2005), Eppinger and Chitkara (2007), Khurana (2007)). Each PD activity can be assigned to one of the four squares and the related action on the same is shown in the figure. Thus, PD activities which are high in coordination needs but low in strategic content can be outsourced but not offshored and similarly PD activities that are high in strategic content but low in coordination needs can be offshored but not outsourced. There can be exceptions to the above, e.g. Pitney Bowes’ relationship with Canon, and these need to be managed carefully.

Our theory and model developed over the remainder of this section address the issue of the firm that is seeking to set up an offshore location to achieve cost savings. The key difference between modeling for offshoring in such a case and a outsourcing model is that the value proposition in outsourcing extends to the relative incentive structures between the firm and the supplier. In terms of Fig. 1-2, our model developed here addresses the trade-off between top and bottom boxes on the left side (‘make’). We build our model on existing work in OM/PD/Organizations and organization economics literature (similar to Gomes and Joglekar (2008)).

### 3.2.1 OM/PD/Organizations Approach

The Operations Management/Product Development/Organizations (OM/PD/Org.) literature provides two complementary prescriptions with regards to GPD: offshore modular products and improve communication between GPD locations (Srikanth and Puranam (2008a)). This stream can be traced to the seminal work of March and Simon (1958) who stated that there are two generic coordination strategies: coordination by plan and coordination by feedback. Organization planners aim for decomposition to identify standardized interactions between interdependent tasks to achieve coordination by plan. However as uncertainty increases, coordination relies more on
feedback. Thus while modularity achieves coordination by plan, ICT (Information and Communication Technology) tools are used to achieve coordination by feedback (Srikanth and Puranam (2008b)).

The fundamental concern of OM/PD/Org. approach is to ensure that PD programs adhere to or exceed the program timing and/or quality targets (Krishnan et al. (1997), Loch and Terwiesch (1998), Terwiesch et al. (2002)); this stream considers task interdependency and concurrency. As outlined by Allen (1977), increasing the distance between members of a R&D group reduces the chances of them communicating for technical matters. Sosa et al. (2002) found that while firms have found ways to mitigate such hindering effects, there continues to be a detrimental impact of distance separation. In a GPD environment, specially when the geographic distances are large and there exist significant time-zone differences, effectiveness of coordination is challenged (Kraut et al. (2002), Armstrong and Cole (2002)). Hence the proposed way is through reduced need for interactions across locations, implying the offshoring of modular tasks (Sanchez and Mahoney (1996), Baldwin and Clark (2000), Langlois (2002)) or that of ‘task-partitioning’ to ensure minimum interdependence across barriers (von Hippel (1990)) to ensure proper division of labor in the information processing view (Simon (1973)). However this proposal assumes that the interfaces are well identified and defined.

The IT literature has built on Parnas (1972) to identify methods of pursuing modularization. However it may not always be possible to achieve modular structures (Ethiraj and Levinthal (2004)) to aid offshoring in CES. This could be due to the complexity of the system (Simon (1969), Whitney et al. (2004)) or because it may require significant economic and/or technical sacrifices to attain modularity (driven by bounded rationality (March and Simon (1958), Whitney (1996))). So it is necessary to have appropriate means of communication between the various GPD locations and efforts should be made to improve the ICT (Information and Communication Technologies) tools for the same (Kraut et al. (2002)). However, the effectiveness of ICT tools as appropriate and successful channels of communications continues to be debated (Olson and Olson (2000), Olson et al. (2002), Orlikowski (2002)).

In addition, a new area of research, common ground (Srikanth and Puranam (2008a)), is emerging. Common ground between two parties is defined as their net common knowledge, belief and suppositions (Clark (1996)). Common ground can be achieved across locations by relying on shared work procedures, enabling visibility of information across locations and prior shared experience (Srikanth and Puranam (2008a)) or by forging social identities (Kogut and Zander (1996)). This common knowledge helps achieve tacit communication and thus supports coordination efforts.

### 3.2.2 Transaction Costs Approach

Transactions costs theory (TC) as defined by Coase (1937) and Williamson (1975, 1985) looks at firms making the decision between markets and hierarchies based on
3.2. THEORY AND MODEL DEVELOPMENT

Williamson (1975) built on the principle of bounded rationality (Simon (1957)) to say that bounded rationality and opportunism combined to give rise to TC. The decision variable is the governance structure which depends on asset specificity, and uncertainty arising from behavior and environment (Rindfleisch and Heide (1997)). Clemons et al. (1993) outlined thus:

\[
\text{total cost} = \text{production cost} + \text{transaction cost} \\
\text{transaction cost} = \text{coordination cost} + \text{operations risk} + \text{opportunism risk}
\]

Operations risk arises from environmental uncertainty and opportunism risk from behavioral uncertainty. TC theory is primarily concerned with the make/buy conundrum. GPD, when considered independent of the sourcing decision and hence looked at solely as the location decision, can be compared to (3.2.1) above. Since we are considering the in/out-sourcing issue, opportunism risk need not be considered. Coordination costs are incurred during interactions across locations and operations risk arises out of the environmental uncertainty pertaining to offshoring the PD task to a GPD location. This uncertainty leads to differential efficiencies between various locations while performing the same tasks. We need to consider these factors during economic modeling.

3.2.3 Theory Setup

As seen in the earlier sections, modularity and coordination needs are key parameters to be incorporated for modeling GPD organization structures. Modularity is a measure of task interdependence for a given architecture (Gomes and Joglekar (2008)). Given our interest in complex products and systems, it is necessary to perform system architecture studies, which are abstract descriptions of the entities of a system and the relationships between those entities (Whitney et al. (2004)). Architecture determines the amount of interactions (coordination time and cost) between PD tasks which may be performed from different locations.

Brown and Eisenhardt (1995) stated that PD comprises of a set of disciplined problem solving tasks. We extend the interpretation of 'disciplined problem solving' to imply that PD comprises of a set of information processing tasks, in each of which, information is received, generated/processed (problem solving) and disseminated. This follows the information processing view of product development (Galbraith (1973), Tushman and Nadler (1978), Clark and Fujimoto (1991), Adler (1995)). Thus, the associated PD task time comprises of time required for each of these activities related to information processing. We can segregate this task time into work time, where time is spent individually by the responsible group in performing the sub-tasks leading to the deliverables of the task (information generation or disciplined problem solving), and coordination time, where time is spent by the group in obtaining information to
support its efforts, working jointly with other groups towards completing the deliverables of its tasks, dissipating the output of its tasks to other appropriate groups, etc. (receiving and dissipating information). Thus,

\[
\text{task time} = \text{work time} + \text{coordination time}
\]

This information (the division of task time) is obtained through system architecture studies. With respect to (3.2.1), operations risk lies with both work and coordination time as the time required to complete the equivalent amount of work at the GPD location may not be the same as the home location and further, there could exist uncertainty regarding the time taken to complete the PD task. Similar uncertainty may also be experienced with respect to coordination time. Uncertainty needs to be incorporated into GPD modeling.

Given the definition of modularity as an indicator of ‘dis-connectivity’ (Gomes and Joglekar (2008)) and the above segregation of task time, we identify the modularity index of a task in the GPD context as follows:

\[
\text{index of modularity} = \frac{\text{work time}}{\text{work time} + \text{coordination time}}
\]  

(3.2.2)

Thus, a task that has low coordination requirements (in proportion to its work time) is more modular and its index of modularity will tend towards 1. We will use this measure of modularity for the rest of the thesis. We need to highlight here that when we mention higher modularity, increasing modularity, etc. in the rest of the thesis, we would be referring to this index of modularity. None of these terms would imply that the task/department/component is completely modular (index = 1).

Further there are switching costs with every increase in work assignment at the GPD center (coupled with the decrease in work assignment at other locations). These switching costs cover hiring, training, retrenchment, etc. Some of these switching costs may be used to alleviate the challenges of multi-location coordination. Switching costs need to be considered for modeling purposes.

### 3.2.4 Model Development

Consider a firm engaged in the design and development of a product. This product can be decomposed into various components, each of which is required to go through a set of PD activities leading to the market launch of the product (Ulrich and Eppinger (2004)). We represent each of these component-activity combinations by \( n \). The set of all \( n \) is then partitioned into 2 sets \( I \) and \( I' \), where \( I \) comprises of all \( n \) that the firm has identified for offshoring (top-left box in Fig 1-2). Let \( k \) denote the locations where \( n \in I \) can be carried out (current home base, offshore locations, other onshore locations, etc.). \( A_{nkt} \) is the decision variable that indicates that \( n \) is performed at location \( k \) at time \( t \) (\( A_{nkt} \in \{0, 1\} \)). Then, we can model our research question, with
3.2. THEORY AND MODEL DEVELOPMENT

total cost as the value proposition and $V_t$ as the total expected value at time $t$, as:

$$V_t = \min_{A_{nkt}}[[S_t + \sum_k \sum_n \ell_{kt}A_{nkt}(w_{nkt} + c_{nkt})] + e^{-\beta}E[V_{t+1}]] \tag{3.2.3}$$

At time $t$, each $n$ has a work time $w_{nkt}$ and a coordination time $c_{nkt}$ at location $k$. Besides $k$, $c_{nkt}$ also depends on locations $k'$ where all the other $n$ (with which it has to coordinate for successful completion of its tasks) are located. Thus if we designate the home/base location as $k = 1$, an efficiency factor can be used to relate $w_{nkt}$ with the home/base location time $w_{n(k=1)t}$. Similarly we can have efficiency factors relating the coordination time. We will discuss efficiency factors in greater detail in the next section.

$l_{kt}$ is the manpower rate at location $k$ at time $t$. $S_t$ is the sum of all the switching costs incurred at time $t$ when a $n$ undergoes a change in location or an added investment is input to improve productivity. It comprises of hiring costs, retrenchment costs, training costs, etc. $e^{-\beta}$ is the discounting factor. The expectation is with respect to work time and coordination time. Thus our research question is represented as a recursive equation where we look for the appropriate task locations to minimize the total cost over the period under study. Some related constraints are:

$$\sum_k A_{nkt} = 1 \quad \forall i, k, t \tag{3.2.4}$$

$$c_{nkt} = \sum_{n'} \sum_{k'} c_{nn'kk't} \quad \forall n', n, k, k', t \tag{3.2.5}$$

other applicable constraints \tag{3.2.6}

(3.2.4) ensures each $n$ is only performed at a single location at time $t$. Thus, the above is equivalent to the work location problem seen in optimization literature (since we have specified $A_{nkt} \in \{0, 1\}$). The above formulation can be generalized to a work distribution problem by taking $A_{nkt} \in [0, 1]$, i.e. $A_{nkt}$ is continuous in $[0, 1]$. (3.2.5) defines the total coordination time of $n$ at location $k$ at time $t$. We observe from this equation that the coordination time is, thus, also dependent on the location $k'$ of all other $n'$ with whom $n$ has to coordinate. (3.2.6) is a set of all other applicable constraints that are required to be fulfilled, e.g. all work and coordination needs are fulfilled, capacity constraints (absolute and change across time periods), budget constraints on expansion/retrenchment, preference relationships between tasks that are to be offshored, etc. We will identify a few of these during our empirical exercise in section 3.3.

Now suppose $w_{n(k=home)t}$ is the total time required to complete the work at home location for task $(i, j)$ at time $t$. Then,

$$w_{nkt} \times \phi_{nkt} = w_{n(k=home)t} \quad \forall n, k, t \tag{3.2.7}$$
where $\phi_{nkt}$ is the relative efficiency of doing task $n$ at location $k$ at time $t$. The
efficiency factor is relative to the home location (Sobrero and Roberts (2001)). This
can also be explained as the 'stickiness' (von Hippel (1994), Srikanth and Puranam
(2008b)) of the work, where stickiness is the incremental expenditure required to
transfer that problem solving capability. Though there may exist related capabilities
in the GPD location, knowledge specific to the firm may not exist (Kogut and Zander
(1992)), thus leading to efficiency differences compared to the home location. Such
inability to transfer the home base efficiency to GPD location can also be attributed to
human asset specificity (Williamson (1985), Zaheer and Venkatraman (1994)) wherein
the specialized human skills that have been generated through learning by doing over
many years at the home location cannot be transferred or replicated at the GPD
location immediately. Similarly, for coordination time, we have

$$c_{nk,n'k',t} \times \theta_{nk,n'k',t} \geq c_{n,n,t} \quad \forall n, n', t \quad (3.2.8)$$

$$c_{nk} = \sum_{n'} \sum_{k'} c_{nk,n'k',t} \quad \forall n, k, t \quad (3.2.9)$$

where $\theta_{nk,n'k',t}$ is the relative efficiency of coordination between tasks $n$ and $n'$, which
are at locations $k$ and $k'$ respectively at time $t$. It is relative to coordination time
required between the same tasks when both are done at the home location, i.e. $k = k' = \text{home/base location}$, at time $t$. (3.2.9) defines $c_{nk}$ which is used in (3.2.3).
Thus (3.2.7) and (3.2.8) ensure that all the work and coordination requirements are
met at all time $t$. However, it builds on the assumption that the firm architecture
remains constant. (3.2.7) and (3.2.8) can be varied to incorporate changes in total
task content and architecture changes, if any. With repetitions of the job, the GPD
locations learn by doing (Argote (1999)). The efficiency factors $\phi_{nkt}$ and $\theta_{nk,n'k',t}$
evolve over time based on these learning effects.

The above formulation includes all the factors that we have discussed. The actual
work distribution/assignment will depend on the relative work time and coordination
time requirements of each $n$. While the above formulation is primarily based with cost
as the decision factor, it is possible to extend it to other factors that drive a firm’s
GPD efforts. Adaptation to local market needs, aggregation for a market region,
and competence seeking can be built in through appropriate constraints on $A_{nkt}$ and
capacity constraints. Similarly, hedging scenarios can be studied through changes in
$w_{nt}$ and $c_{n,n',t}$ in equations (3.2.7) and (3.2.8) respectively.

The above formulation represents a real options setup (Dixit and Pindyck (1994),
Trigeorgis (1996)). By starting the GPD process by offshoring the first task, the
firm creates the option of offshoring further tasks (it has the opportunity but not the
obligation). Offshoring the first task allows the next task to be offshored to the same
location with spillover benefits or learning effects from doing the first task (Schilling
et al. (2003)). Real option problems have been studied in detail primarily through
dynamic programming and contingent claim analysis. Approaches to address similar
models have included the use of queuing theory, stochastic knapsack problems, index policies using dynamic programming, etc. However, the interdependence (interactions) between tasks violates the assumptions in most of these formulations (require tasks to be independent).

A common approach to such problems (task selection, i.e. \( A_{ntt} \in \{0,1\} \)) is through the use of index policies (bandit class of problems). The multi-armed bandit problem has been shown to be polynomial-time solvable using the Gittins Index (Gittins and Jones (1972)). However, a critical assumption for the multi-armed bandit and the restless bandit (the task’s reward structure changes even when not acted upon), which has been shown to be PSPACE-hard (Papadimitriou and Tsitsiklis (1999)), is that the tasks are independent of each other. This assumption is not valid in our case since we are dealing with complex systems where change in location \( k \) for a \( n \) may result in change in coordination time and thus affect the task time of other tasks. Our problem falls under the category of generalized bandit problems which have no known general solutions. Literature on the same (Nash (1980)) assumes separability of tasks to define indices.

Model formulation (3.2.3) is very general. It can be used to identify work allocation/distribution when a new offshore development center is being setup or when seeking a more efficient PD organization structure. The key challenges when solving a problem using this formulation are: (a) identifying and collating the appropriate data (the inter-dependencies), and (b) managing the complexity of the problem. In the next section we show a methodology to restructure the existing work distribution in an industrial setting, using the above formulation, to minimize total cost. We outline the data required, its generation, and then a transformation to solve the formulation.

3.3 Organizing GPD at Nokia

(per agreement with Nokia, organization names have been altered and data scaled for confidentiality purposes)

Nokia is involved in the design, development, manufacture and sale of mobile phones and related services. Their product has evolved from a device in the 1990s to include more features and significant associated services. Our research is based at a division of Nokia that we identify as the High-End devices division. This division comprises of the Hardware (A) and Software (B) business units. These business units comprise of departments that are spread globally. We segregated these departments between those that were flexible to re-organization (j) and those that were not (d). Business unit A had 10 j and a single d department. Business unit B comprises of a single d department.

The initial expansion of the High-End devices division beyond Finland \( k = 1 \), the home location, was in search of competencies and development capacity. This
had led to development centers at various global locations \((k = 2, 3, 4, 5)\) with each department having its own work distribution across locations \(m_{jk}, m_{dk}\). With the evolution of the internet and development of digital design tools, the High-End division set up another development center \((k = 6)\), the low cost location, transferring work responsibility of certain \(j\) departments there. This development center had significantly lower manpower costs with respect to the other locations. Though this development center was in its third year of operations, the High-End devices continued to face significant difficulties in managing development activities within the new center and between the new center and other development centers. The High-End division was looking at reorganizing the work distribution across locations with an intent to minimize the total cost over a planning period of 5 years.

**PDD Process:** The High-End devices division is involved in many programs simultaneously. Each program’s PDD process (Fig. 3-1) comprises of range planning, product definition, and product development phases. While there exist several formal and informal reviews through the earlier phases, the stage-gate process (Cooper (1993)) starts with the product development phase. The planning phase is calendar based and common across products. It ends in December (year \(t\)) with the confirmed launch plans for \(t + 2\) year. It also schedules the resources for all the products under development. At this stage, the program is either notified as a complex product \((a)\) or a standard product \((b)\) program \((a + b = e)\). The ratio \(a/b\) and \(e\) are maintained constant by the division for planning and execution purposes. The definition phase involves identification of the product characteristics and culminates with product definition and product architecture freeze. There could be a time gap between completion of planning phase and start of definition phase. The product development phase starts on completion of product definition, and ends when the product is ready for market launch, wherein the product is customized per respective market needs. Our exercise involved the range planning, product definition, and product development phases.

![Figure 3-1: Nokia Product Development Process](image)

**3.3.1 Problem Definition**

We could relate the problem with our formulation for organizing global product development (3.2.3). The tradeoff relates to lower costs (due to lower manpower rates)
3.3. ORGANIZING GPD AT NOKIA

of doing PDD work at some locations but is associated with the caveat of higher task time and coordination challenges across locations. In discussions with Nokia, we agreed on using net cost as the criterion for evaluation. Our objective involved identifying the global distribution of work for the various departments over a planning period of 5 years (each year is a time period). We needed to develop the model to include specific Nokia related constraints (e.g. location based content, etc.).

We applied the model developed earlier in this chapter (3.2.3) to address Nokia’s dilemma. We identified and measured/derived the related variables and captured the learning dynamics. We modified our recursive equation (3.2.3) for this situation, and optimized for various scenarios. We used our definition of modularity (3.2.2) to make observations on the results obtained. Thus, we were able to address the two research questions that we had posed: How does a firm optimally structure the global work distribution, over time, of its product development organization? How does the firm’s architecture affect these work distribution decisions? By firm’s architecture, we imply the product, process or hybrid architecture that can be used for system decomposition to help the firm identify the task to be offshored.

The High-End devices division was looking at work distribution, across locations, for each department. This implied that we had to consider the aggregate of all programs that the division is involved in each year. Thus, in a hierarchical sense (Anderson and Joglekar (2005)), we were looking at identifying the work distribution at a ‘strategic → operational’ level. Actual work distribution for each program would be derived based on simulation studies/manpower availability and would constitute the ‘tactical’ level. For each type of program (complex product or standard product), the High-End devices division has identified the manpower allocation for each department for each phase, and for the product development phase, the manpower allocation for each stage gate has been identified. Thus our problem relates to work distribution of the total manpower, which is the aggregate of the allocation for all departments for all programs in a given year.

At the program level, there will be a higher level of uncertainty relating to the specific nuances of the program. Such uncertainty could lead to different departments needing to get involved in unplanned coordination (coordination by feedback (March and Simon (1958))), perhaps requiring temporary allocation of extra work time and coordination time. These are balanced by transferring engineering staff from other programs or by hiring temporary staff. At the organization level, the aggregate planning considers the average coordination that is required by each type of program (coordination by plan (March and Simon (1958))). Hence, our study reduces (3.2.3) to a multi-period mathematical programming (deterministic) formulation. The tradeoff relates to lower costs (due to lower manpower rates) of doing PDD work at some locations but is associated with the caveat of higher task time and coordination challenges across locations.

Aggregating through the program level data, we could identify the total manpower for each department for each phase/stage-gate. However, per (3.2.3), we needed to
identify the work time and coordination time separately, within the total manpower allocation. Since doing so at the aggregate level was both difficult and susceptible to errors, it was necessary to identify the same at the program level and then aggregate for the division.

3.4 Data Development

The foundation of the High-End devices division’s PDD process is based on well identified deliverables for each phase/stage gate. The PDD process represents the process-flow architecture of the organization. It identifies the list of tasks that are required for a successful PDD. We also needed to understand the information flow/dependencies between these tasks to enable the differentiation between work and coordination time. So we opted for a process-flow DSM (Browning (2002), Chen et al. (2003)). Design structure matrix (DSM) (Steward (1981), Eppinger et al. (1994)) is a useful tool to decompose the architecture of a system, either by product, process, team/group, hybrid of these, etc. It is a project modeling tool which represents the relationships between project tasks or sub-systems/components in a matrix form. Here we develop the process-flow DSM for the range planning, product definition and product development phases.

The High-End devices division identified a number of personnel from various departments for us to interview. We had two rounds of interviews, split by a month in between. In the first round (unstructured interviews), we interviewed 15 people for 60-120 minutes each. We asked them to identify the respective deliverables for their departments for each phase/stage gate and the tasks (i) required to be done for the same. They were also asked to identify, for each task, the source of information leading to the task and the destination of the output of the task, and the difficulty in obtaining this information. We collated this data to create a draft process-flow DSM of 160 tasks. The department(s) responsible for each task was identified. In certain cases multiple departments were assigned. This was done when it was deemed that there was significant difficulty in information transfer or when multiple departments were required to work jointly.

In the next round of interviews, we reviewed the draft DSM with the same personnel: 7 personal interviews of approximately 60 minutes each, group interviews of approximately 12 hours and a full-day workshop. Based on these interviews and the workshop, we developed a modified process flow DSM (Fig. 3-2) comprising of 214 tasks. 90 of these tasks required significant interactions between departments or had to be done jointly. The DSM had a total of 598 marks (dependencies), i.e. approximately 2.79 dependencies per task.

We now had the process flow DSM and the data for manpower allocated to each department for each phase/stage gate. We then met with representatives from the various departments and those from the planning group. We asked them to distribute
3.4. DATA DEVELOPMENT

the manpower time allocation, assuming that all the manpower is based at the home location $k = 1$, between the various tasks that the department is involved in each phase/stage gate, and for each task, distribute this task time between work time and coordination time whenever multiple departments were involved for the tasks (Fig. 3-3). This split of task time to work time ($w_{ij}$) and coordination time ($c_{ij}$, $c_{id}$, $c_{id'}$) data was developed by them based on their experience from various programs through the years. We resolved differences through a final full-day workshop. To resolve the differences, we needed to understand that $c_{ij'} = \max (c_{ij}, c_{ij'})$, i.e. coordination time is maximum of the coordination time needed by the departments involved for successful completion of the task. We had the average work time and coordination time split. However it is necessary to recognize here that not every program follows this split exactly.

Then, with the process flow DSM (Fig. 3-2) and the work time and coordination time data (Fig. 3-3), we did an organization mapping exercise (Pimmler and Eppinger (1994)) to develop an organization (department) numerical DSM (Fig. 3-4). We determined each department’s work time as $w_j = \sum_i w_{ij}$ and coordination time with every other department as $c_{ij'} = \sum_i c_{ij'}$ ($j \neq j'$) and $c_{id} = \sum_i c_{ijd}$. This was done for each of the program types and then weight added with the respective number of programs of each type/year ($a, b$).

The left column in Fig. 3-4 lists the respective departments of business units
CHAPTER 3. OPTIMAL STRUCTURING OF GPD ORGANIZATION.

Figure 3-3: Work Time and Coordination Time for PDD Process Tasks (units: man-years)

A and B, and they are repeated in the top row. Any numerical value that is non-diagonal in the nDSM denotes the total coordination time between the respective departments $c_{ij}$ and $c_{jd}$. Numerical values along the diagonal represent the work time for the department $w_j$. Department A-PfM and business unit B are constrained against changes ($d$ departments) in their current work content distribution and hence do not contain values in the diagonal against them. The right most column identifies the index of modularity for each of the $j$ departments per (3.2.2). This nDSM is a symmetric square matrix (interactions between two departments is the same) and represents the architecture of the High-End devices division.

3.4.1 Cost Data

For each location $k$, we identified the various cost data which we were advised to consider as constant over the planning horizon. These include

- $l_k$, the manpower rate at location $k$
- $SU_k$, the cost of increasing manpower between successive time-periods at location $k$, per man-year
- $SD_k$, the cost of decreasing manpower between successive time-periods at location $k$, per man-year
- $SUD_{jk}$, $SUD_{dk}$, the cost of increasing manpower between successive time-periods for departments $j$ and $d$ at location $k$, per man-year

3.4.2 Efficiency Differences

Nokia observed differences in work and co-ordination time across locations. The same work takes different time for completion in different locations (also observed by Herbsleb and Mockus (2003)). Through discussions and data available with their
planning group and past program leaders, we could establish the relative work time efficiencies between locations by department, \( \phi_{jk} \). It was assumed that when an activity is carried out at the department level, cross-location coordination challenges are captured within this factor (presence of strong department deliverable culture through a strong department project leader (Wheelwright and Clark (1992))). The relative efficiencies are as shown in Fig. 3-5.

Similar challenges are faced in coordination between departments, particularly when they are situated in different locations. These challenges vary depending on
the respective locations. Through discussions with the same group (as for work efficiencies), we were able to rank $\theta_{kk'}$, the relative efficiency when the departments engaged in coordination are located at k and $k'$ respectively (though $\theta_{jk, k'}$ would have been the ideal data ($j \neq j'$)). Thus, while the work time efficiency data was obtained on an absolute basis, data for coordination time was on a ranked basis. We ranked the various combinations of $(k, k')$, 15 combinations when $k \neq k'$ and 6 when $k = k'$, on a 4 point scale. Through discussions we understood that the 1-4 rank scale transformed to a doubling of the time required for coordination, though not linearly. We used a convex function (details in Appendix A) to transform the same from scaled numbers to absolute efficiencies. Thus we were able to establish $\theta_{kk'}$. We confirmed our findings with Nokia personnel. An example of this data is shown in Fig. 3-6.

<table>
<thead>
<tr>
<th>$\theta_{kk'}$</th>
<th>relative coordination efficiencies at t=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>k/k'</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>0.870</td>
</tr>
<tr>
<td>3</td>
<td>0.870</td>
</tr>
<tr>
<td>4</td>
<td>0.706</td>
</tr>
<tr>
<td>5</td>
<td>0.706</td>
</tr>
<tr>
<td>6</td>
<td>0.503</td>
</tr>
</tbody>
</table>

Figure 3-6: Coordination Time Relative Efficiencies (at time t=0)

In this way, we could now relate the actual manpower distribution across locations since we have department work and coordination time data (Fig. 3-4) at the home location levels and the respective efficiency levels.

3.4.3 Learning Effects

As established in literature, through repeated work, organizations learn and are able to improve their output (Argote (1999)). Though most literature has alluded to the same for manufacturing operations, the same has also been established for service industries (Boone and Ganeshan (2001)). Similarly, product development centers benefit from the learning curve with repeated work and coordination (ill structured problems in Simon (1973), von Hippel and Tyre (1995)). Nokia’s PDD centers experience the same benefits. We built in the learning effect through the efficiency factors defined in the previous section.

**Learning in work time:** We captured the learning effect in the work time as

$$\phi_{jk}(T_{k+t}) = \frac{\phi_{jk}(T_k)}{(T_{k+t}/T_k)^{-r_k}}$$
3.4. DATA DEVELOPMENT

where $T_k$ is the number of years that location $k$ has been operating as a Nokia PDD center and $r_k$ is the learning rate measured at that location. Relative work time efficiency factors evolve with time $t$. We consider each year as a time period (consistent with Nokia’s product programs which are spread over a period of one year). We initialize as $\phi_{jk}(T_k) = \phi_{jk}$, the data provided by Nokia. Since most Nokia PDD centers have been functioning for a number of years ($T_k$ much greater than $t$), the benefits of learning are not significantly visible or measurable year to year. However, learning effects were visible, experienced and considered for the GPD location $k = 6$. There could be training-induced efficiency improvements at the other locations, but these would involve investments and were not considered.

**Learning in coordination time:** Similar to work time, we capture learning benefits in coordination time through

$$\theta_{kk'}(T_k + t) = \frac{\theta_{k(T_k)k'(T_k')}}{\max \left( (\frac{T_{k+}t}{T_k})^{-r_k}, (\frac{T_{k'}k'}{T_{k'}})^{-r_{k'}} \right)}$$

We initialize $\theta_{k(T_k)k'(T_k')} = \theta_{kk'}$ (the data available), and observe that since most locations have been a Nokia PDD center for many years ($T_k$ much greater than $t$), learning effects are observable for location $k = 6$ related coordination only. This assumes that coordination tools and mechanism remain the same as currently practiced. There could be improvements in coordination through new practices and methodologies which have not been factored in, but that would involve incremental investments in process improvements.

3.4.4 Current State ($t = 0$) Work and Coordination Time

We had obtained the work time $w_j$ and coordination time $c_{jj'}$ and $c_{jd}$ in the organization nDSM (Fig. 3-4). This represented the time required if all the work was done at home location $k = 1$. However Nokia’s PDD activities are distributed globally. Nokia provided us with $m_{jk}$ and $m_{dk}$, the proportion of task time that department $j/d$ does at location $k$, at home base efficiency levels. Thus we were able to identify the current state work time and coordination time using:

$$w_{jk} = \frac{w_j . m_{jk}}{\phi_{jk}} \quad \text{and} \quad c_{jkj'k'} = \frac{c_{jj'} . m_{jk} . m_{j'k'}}{\theta_{kk'}}$$

This transforms the organization (department) nDSM (Fig. 3-4) to an organization (department-location) nDSM (Fig. 3-7), providing the initialization or current state conditions:

$$w_{jk}(t=0) = w_{jk} \quad \text{and} \quad c_{jkj'k'}(t=0) = c_{jkj'k'}$$

We found these comparable to the existing manpower allocations across departments
CHAPTER 3. OPTIMAL STRUCTURING OF GPD ORGANIZATION.

Figure 3-7: Organization (department and location) nDSM

![Image of organization diagram]

and locations. Fig. 3-8 summarizes the steps that were followed.

Figure 3-8: Data Development Methodology

![Image showing steps of data development]

3.5 Model and Results

3.5.1 Problem Formulation

In (3.2.3) we had $A_{nkt}$ as the decision variable as $w_{nkt}$ and $c_{nkt}$ were assumed to be known. Now we have the known efficiency factors $\phi_{jk}(T_k+t)$ and $\theta_{kt'}(T_k+t)$ and the total work and coordination to be completed at each time epoch $t$, i.e. $w_j$ and $c_{jj'}$. Thus we now need to identify the work and coordination allocation at each $t$ (similar to the case where $A_{nkt} \in [0, 1]$). So our decision variables are $w_{jk}$, $c_{jk'k't}$ and $c_{dkjkt'}$ with (3.5.2) and (3.5.3) ensuring that all work/coordination is completed (3.2.4). Given
3.5. MODEL AND RESULTS

our objective of minimizing cost, we formulate our problem for the planning horizon as:

\[
\text{Min} \quad \sum_{t=1}^{5} e^{-\beta t} \left( \sum_{k} \left( \sum_{j} (l_k \cdot (w_{jkt} + c_{jkt})) + \sum_{d} (l_d \cdot c_{dkt}) \right) \right) \\
\quad + \sum_{t=1}^{5} e^{-\beta(t-1)} \left( \sum_{k} S_{U_k} \cdot \max\left( \left( \sum_{j} (w_{jkt} + c_{jkt} - w_{jk(t-1)} - c_{jk(t-1)}) + \sum_{d} (c_{dkt} - c_{dk(t-1)}) \right), 0 \right) \right) \\
\quad + \sum_{t=1}^{5} e^{-\beta(t-1)} \left( \sum_{k} S_{D_k} \cdot \max\left( \left( \sum_{j} (w_{jk(t-1)} + c_{jk(t-1)} - w_{jkt} - c_{jkt}) + \sum_{d} (c_{dk(t-1)} - c_{dkt}) \right), 0 \right) \right) \\
\quad + \sum_{t=1}^{5} e^{-\beta(t-1)} \left( \sum_{k} S_{U_{dk}} \cdot \max\left( \left( \sum_{j} (w_{jkt} - w_{jkt} - c_{jkt} - c_{jk(t-1)}), 0 \right) \right) \right) \\
\quad + \sum_{t=1}^{5} \sum_{k} \sum_{d} S_{U_{dk}} \cdot \max\left( \left( \sum_{j} (w_{jkt} - w_{jkt} - c_{jkt} - c_{jk(t-1)}), 0 \right) \right) \\
\text{s.t.} \quad \sum_{j'} \sum_{k'} c_{jkj'k't} = c_{jkt} \quad \forall j, k, t & \quad \sum_{j} \sum_{k'} C_{dkjk't} = c_{dkt} \quad \forall d, k, t (3.5.1) \\
\sum_{k} w_{jkt} \times \phi_{jkt} \geq w_{t} \quad \forall j, t \quad (3.5.2) \\
\sum_{k} \sum_{k'} c_{jk(k'k')t} \times \theta_{kk'} \geq c_{j} \quad \forall j, j', t \\
\quad \& \quad \sum_{k} \sum_{k'} c_{jk(k'k')t} \times \theta_{kk'} \geq c_{j} \quad \forall j, d, t \quad (3.5.3) \\
\sum_{k} \frac{(c_{jk(j'k')t} \times \theta_{kk't})}{w_{jkt} \times \phi_{jkt}} \geq \frac{c_{j}}{w_{j}} \quad \forall (j, k'), k, t \quad (3.5.4) \\
\sum_{k} \frac{(c_{jkdk't} \times \theta_{kk't})}{w_{jkt} \times \phi_{jkt}} \geq \frac{c_{j}}{w_{j}} \quad \forall (j, d), k, t \quad (3.5.5) \\
\text{Capacity and non-negativity constraints} \quad (3.5.6) \\
\text{Competence preserving constraints} \quad (3.5.7) \\
\]

The objective function gives the total cost to be minimized over the planning horizon. Each of the four terms has a part corresponding to the \(j\) (flexible) and the \(d\) (non-flexible) departments respectively. While the first term looks at the total
manpower costs incurred in each period, the next three terms capture the cost of 
manpower change between time periods (manpower increase at location, manpower 
decrease at location, manpower increase for a department at a location).

Constraints (3.5.1) are definition constraints. Constraints (3.5.2) and (3.5.3) en-
sure that all the work time and coordination time needs are completed. These were 
identified from the Organization (department) nDSM. Thus these requirements are 
defined at home location $k = 1$ efficiency levels.

Architecture constraints (3.5.4) and (3.5.5) introduce the organization architec-
ture. As discussed earlier, any product development task comprises of work and 
coordination time. For any work to be performed, a proportionate amount of coor-
dination needs to be done. We identified this ratio of coordination to be done by the 
department with every other department and the work to be done by the department 
through our organization (department) nDSM. (3.5.4) and (3.5.5) ensure that this 
ratio (at home location $k = 1$ levels) is maintained with every workload distribution. 
The inequality ensures that the minimum coordination needs are met (the direction 
of the inequality is based on the premise that coordination needs have to be met for 
successful product development). In the absence of these constraints, the optimiza-
tion exercise could have allocated the work time and coordination time to different 
locations. The LHS of the constraint is obtained from the Organization (department) 
nDSM (Fig. 3-4). It reflects the organization architecture and is constant.

Constraints (3.5.6), besides the non-negativity constraints, include capacity con-
straints which ensure that the manpower changes at any location, between time-
periods, is constrained. These are of the type:

$$\sum_j (w_{jkt} + c_{jkt}) + \sum_d c_{dkt} \geq x \left( \sum_j (w_{jkt(t-1)} + c_{jkt(t-1)}) + \sum_d c_{dkt(t-1)} \right)$$

$x \leq 1$ would imply that downsizing between successive periods for location $k$ is 
constrained. Similarly with the inequality in the other direction and with $x \geq 1$, the 
upsizing between successive periods can be contained (it may be difficult to expand 
too fast at GPD locations due to non-availability of appropriate manpower, non-
availability of manpower from existing locations to provide startup support, etc.)

Moreover competencies to perform department tasks and activities are developed 
and established at locations that have been PDD centers for a long time. Where 
desired, these competencies are preserved through (3.5.7), which ensures that the 
total task content of certain departments at these locations does not reduce beyond 
desired limits. An example of such an equation is as follows:

$$w_{jkt} \geq y \cdot w_{jkt(t-1)}$$

In the above, work content for a department $j$ at location $k$ is not allowed to reduce 
to less than a fraction $y$ of the work content of the previous period.
Analysis of the Formulation: We linearize the non-linearities in the objective function (present through $\max$ functions) as follows:

$$\min \max (x,0) \quad \text{is linearized as}$$

$$\min g \quad \text{subject to} \quad g \geq x, \quad g \geq 0$$

The constraint set consists of linear equations, thus forming a convex set. The simultaneous presence of a convex constraint set and a linear objective function ensures that the above formulation is reduced to a linear programming problem. This gives two very important implications (Bertsimas and Tsitsiklis (1997)): the problem is now polynomial time solvable and there exists a corner point (unique) solution with no duality gap. Thus, we can develop such problems for a very high number of departments or can solve such problems at the task level rather than at the department level (data availability could be a challenge in that case). In a general case, many firms may use manpower head count in lieu of manpower task time. Then we would have a mixed integer program and scalability and duality gap could be issues. In the case of the High-End devices division, the manpower allocated to each department/location is quite high and hence it was ok not to use integer restrictions (agreed with the division).

### 3.5.2 Optimization Constraints

Since we were running an optimization model, we needed to develop a base case to compare our results against. To develop a base case (called 'Status Quo' (S0)), we calculated the total cost of all the PDD work over the defined planning horizon (5 years), assuming that the current state work distribution is maintained. We included the future expected learning on the work and coordination time at the GPD location. We initiated the location capacity constraint (3.5.6) as follows:

- total work at home location ($k = 1$) cannot reduce by more than 10%/year or 25% over the 5 years
- total work cannot reduce at locations $k = 2,3,4,5$ by more than 10%/year
- total work cannot increase at GPD location by more than 15%/year

We started by running the optimization for the case where a decision is made only once and the PDD organization is constant between time periods $t = 1$ and $t = 5$. We called this the 'Single Decision' (S1) case. We then allowed the work assignment to change in every period ('Existing Dept-Loc' or Case S2). Next we introduced the competence preserving constraint (3.5.7) wherein the work content for any department at any location cannot reduce, at any time period, to less than 50% of existing content. ('Competence Preserving' or Case S3). In each of the above cases it
was assumed that only the current departments that are present at the GPD location will continue there. So, in the next case, we assumed that all the departments can expand to the GPD location (‘Global Expansion’ or Case S4), requiring us to develop new efficiency factors (we assumed that the learning rates carried over).

3.5.3 Optimization Results

Our results from the above cases are as follows:

<table>
<thead>
<tr>
<th>Case</th>
<th>S1 single-period existing dept.-loc.</th>
<th>S2 multi-period existing dept.-loc.</th>
<th>S3 multi-period competence preserving</th>
<th>S4 multi-period GPD expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>5.89%</td>
<td>7.77%</td>
<td>7.01%</td>
<td>8.55%</td>
</tr>
</tbody>
</table>

Figure 3-9: Optimization Results (cost savings from S0 case)

We observed significant cost savings over the case of continuing with the current work/capacity distribution (Status Quo). The only other possible comparison with any proposed policy existing in literature would be to use the prescription of offshoring modular products first. This is not a viable case to compute as it would involve, after ranking the departments in terms of modularity, transferring the complete contents of the most ‘modular’ department to the GPD location till some constraint becomes active. But what does it replace? From which location does this task get re-assigned? Thus all our cost comparisons were with respect to the case of ‘Status Quo’ S0.

Our cost reductions (savings) translate to significant amounts for Nokia. We observe that most cost savings are captured in the first period changes itself (5.89% in case S1). Thereafter the cost savings increase as changes are allowed in subsequent periods (case S2); there is reduction when the competence preserving constraints are introduced (case S3), and finally there are more cost savings through developing the GPD center for all departments (S4).

3.5.4 Observations

As we are using an optimization model, we can make observations from the results. We cannot make generalizable conclusions as the data is specific to the firm under study. We next outline our observations. Two of these conform to existing literature. However the third observation highlights a new trade-off leading to a subsequent research question.

Earlier we had defined modularity as the state of ‘dis-connectivity’ of a component/process/task in the architecture and identified its measure for GPD as the ratio
of work time to task time (3.2.2). We now apply this measure to the data that we have with Nokia. In the organization (department) nDSM (Fig. 3-4), we identify the work time and coordination time for each department. Thus we are able to identify index of modularity for each department. We rank the departments by this index as ModRk1, ModRk2,...ModRk10, with department labeled ModRk1 having the highest modularity index. This data is with base location efficiency. We need to consider the organization (department-location) nDSM (Fig. 3-7) to identify the modularity for the existing department location capacity distribution. Further given that the manpower rates vary across locations, cost considerations also needed to be considered. So we consider the Status Quo case identified above (derived from the above nDSM and the manpower rates) and identify the total work time and total coordination time costs for Nokia’s High-End division. We observe this ratio to be approximately 70:30 (69.84 : 30.16) between work time and coordination time costs. We will use the above identified measures, ranks and ratio in subsequent analysis.

**Obs 1: Reduction of coordination content and costs**

In Fig. 3-10, the cost changes for cases S1, S2, S3, and S4 with respect to Status Quo have been separated out, e.g. we observe that for case S2, the cost reduction of 7.77% comprises of cost increase of 2.76% (2.59% + 0.17%) due to fixed costs (costs incurred in restructuring (hiring, retrenchment, department setup, etc.) at the various locations) and cost reduction of 6.63% and 3.90% on account of work time cost and coordination time cost reductions respectively. These reductions correspond to reductions in work time cost and coordination time cost by 9.50% and 12.92% respectively, i.e. 9.50% work time cost reduction contributes to 6.63% reduction to the total cost under consideration.

<table>
<thead>
<tr>
<th>Analysis of changes in total costs</th>
<th>Case S1</th>
<th>Case S2</th>
<th>Case S3</th>
<th>Case S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hiring, retrenchment, etc. in locations k = 1,2,3,4,5</td>
<td>-0.99%</td>
<td>-2.59%</td>
<td>-2.52%</td>
<td>-2.56%</td>
</tr>
<tr>
<td>Hiring, retrenchment, etc. at GPO location k = 6</td>
<td>-0.01%</td>
<td>-0.17%</td>
<td>-0.15%</td>
<td>-0.29%</td>
</tr>
<tr>
<td>Variable Costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work time costs</td>
<td>3.97%</td>
<td>6.63%</td>
<td>5.35%</td>
<td>6.88%</td>
</tr>
<tr>
<td>Coordination time costs</td>
<td>2.92%</td>
<td>3.90%</td>
<td>4.33%</td>
<td>4.52%</td>
</tr>
<tr>
<td>Total cost change</td>
<td>5.89%</td>
<td>7.77%</td>
<td>7.01%</td>
<td>8.55%</td>
</tr>
</tbody>
</table>

| Cost reductions in                |         |         |         |         |
| Work time costs                   | 5.68%   | 9.50%   | 7.66%   | 9.85%   |
| Coordination time costs           | 9.68%   | 12.92%  | 14.35%  | 15.01%  |

Figure 3-10: Analysis of cost reductions

We had earlier seen that the work time cost to coordination time cost is in the ratio of 70:30 in the existing ('Status Quo') work distribution. However, the cost reduction contributions for case S2 is in the ratio of 62:38 (6.63% : 3.90%). The corresponding ratio for cases S1, S3 and S4 are 58:42, 55:45 and 60:40 respectively. The corresponding reductions in work time and coordination time costs are 5.68%
and 9.68% for case S1, 7.7% and 14.3% for case S3 and 9.8% and 15% for case S4 respectively. We observe that the proportionate reduction in coordination time cost is more than that of work time cost. In the resulting organization structures, the ratio of work time cost to coordination time cost increases, implying that the organization tries to increase its ‘work assignment’ modularity (reduce coordination content). This supports the literature prescriptions to prioritize offshoring of modular tasks (Sanchez and Mahoney (1996), Baldwin and Clark (2000)). It is important to note here that the ‘organization’ modularity (Fig. 3-4) does not change. ‘Modularity’ changes as discussed here relate to the final work time and coordination time per varying work assignments.

**Obs 2: Changes in work assignment at locations**

We had identified constraints for changes allowed in the work assignment for each location (between successive time periods). In Fig. 3-11 we identify the changes in work assignment at each location (quantum of work given to that location) over time. Along the X-axis we have the time periods $t = 1, 2, 3, 4, 5$. Along the Y-axis we have the % change in work assignment to the location with respect to the previous year. At time $t = 1$, we have the change in work assignment between $t = 0$ and $t = 1$. We develop this graph for each of the cases S1, S2, S3, and S4.

We observe that the year on year change in work assignment constraint is active for locations $k = 2, 3, 4, 5$ and the GPD location $k = 6$ at various time periods in each of the cases. For the base (home) location $k = 1$, it is not active during any time period. The difference between the graphs is due to the different conditions under which the optimization models were run. The constraint corresponding to the year to year change allowed in work assignment for the various locations ceases to be active when the cost savings from work time and coordination time changes cannot payback the incremental costs for capacity relocation.

Interestingly, in S1, S2 and S3 cases, though this constraint is active in locations $k = 2, 3, 4, 5$ at time $t = 1$, the capacity at the Base and GPD locations does not increase. On review of the relevant data we find that there is a ‘re-organization’ of task allocation/capacity distribution. Thus all the work and coordination needs are met through re-assignment. Only in case S4 is the capacity transferred to the GPD location (since other departments can be expanded there in this case) at $t = 1$. Similar to Obs 1, we observe that the coordination time cost between time periods $t = 0$ and $t = 1$ reduces, relatively, more than the work time cost for each case. While the work time cost reduces in the range 3.44% to 5.62% between $t = 0$ and $t = 1$, the coordination time cost reduces in the range 11.29% to 13.48%. Thus we can say that the organization prioritizes re-structuring to reduce coordination requirements (improve modularity) before assigning capacity to the low cost rate GPD location (adds to Obs 1 earlier).
3.5. MODEL AND RESULTS

Figure 3-11: Work assignment changes at locations over time

Obs 3: GPD work assignment for each department

The earlier observations support literature prescriptions on prioritizing modular tasks/components for offshoring. However, as shown in Fig. 3-12, this may not always represent the optimal solution for organizing product development organizations for complex products.

We observe the total work allocation by each department to the GPD location in Fig. 3-12. Per earlier definition, we could identify the modularity of each department from the organization (department) nDSM (Fig. 3-4). On ranking the departments by their modularity, with ModRk 1 representing the most modular department and ModRk 10 the least modular department, we observe that departments with ranks 4, 8, 9, and 10 were present at the GPD location at time $t = 0$ (existing conditions). Thus under cases S2 and S3, these would remain the only departments at the GPD location. Other departments would expand to the GPD location in case S4.

Our optimization results show that while the content offshored to the GPD location increases for the departments ranked 4, 8, and 10, it actually reduces for the department ranked 9. This non-monotonic behavior does not support existing literature which predicts otherwise (Sanchez and Mahoney (1996), Baldwin and Clark (2000)). On investigating this phenomenon further, we observed that ModRk 9 de-
CHAPTER 3. OPTIMAL STRUCTURING OF GPD ORGANIZATION.

Figure 3-12: GPD content over time (for each department)

The department’s coordination needs with other departments were similar to those of ModRk 8 and ModRk 10 departments. The difference was in the relative work efficiency factor (Fig. 3-5). It was 0.286 for ModRk 9 department at the GPD location. The corresponding efficiency factor was 0.6 for the other departments at \( t = 0 \). This significant efficiency difference for ModRk 9 department caused most work to be concentrated at the base location, though this department requires coordination with various departments which are distributed across all the locations.

As seen above, the efficiency difference also drives the offshoring content. This implies that the modularity based offshoring prescription is not always valid. Efficiency differences play a critical role. This behavior, understood through the data details, has not been explored significantly in literature (Anderson et al. (2008)). Efficiency differences exist as it may be very difficult to transfer the full set of competencies to another location (Kogut and Zander (1992), von Hippel (1994)). A lot of it can be attributed to the differences in terms of culture and practices between the two locations (Fine (1998)). It may be possible to improve upon the efficiency differences over time through learning effects. This observation leads us to frame a further research question: How does the work time and coordination time of a task change (efficiency differences) when it is transferred to an offshore product de-
Development center? How does a firm spread its offshoring efforts between the factors that contribute to these efficiency differences? We explore this question further through a stylized model in the next chapter.

### 3.6 Sensitivity Analysis

Our methodology and modeling efforts have involved a lot of data and a number of constraints. As outlined earlier, many of these constraints are driven by the strategic considerations of the firm, e.g. capacity changes at a location. While a number of combinations of data and constraints can be studied for sensitivity analysis, we discuss a few of them here.

#### 3.6.1 Capacity Change Constraints

<table>
<thead>
<tr>
<th>Locations</th>
<th>Single Decision (54)</th>
<th>Existing Loc (53)</th>
<th>Competence Preserving (53)</th>
<th>Global Expansion (54)</th>
</tr>
</thead>
<tbody>
<tr>
<td>k = 2, 3, 4, 5</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
</tr>
<tr>
<td>k = 2, 3, 4, 5</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
</tr>
<tr>
<td>k = 2, 3, 4, 5</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
</tr>
<tr>
<td>k = 2, 3, 4, 5</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
<td>x ≤ y</td>
</tr>
</tbody>
</table>

Figure 3-13: Active capacity constraints

As seen in Obs 2 (Fig. 3-11) and in Fig. 3-13, capacity change constraints of certain locations are active during some time periods. These capacity change constraints are developed as part of the firm’s strategic priorities and decisions. With 6 locations and 5 time periods, there are many combinations of sensitivity studies that could be done. We study sensitivity of the optimal cost with respect to changes in the capacity change constraints in three different cases.

**Locations k = 2, 3, 4, 5**

As observed in Fig. 3-13, the capacity constraints for locations \(k = 2, 3, 4, 5\) are active over multiple time periods. This capacity constraint is 10%, i.e. the total capacity at any location cannot reduce by more than 10% year on year. Though the relative work time efficiencies differ across these locations, we group them together as we expect the firm to follow a common policy across these locations. We performed sensitivity analysis changing the capacity constraint to 9%, 11% and 20%. The results are shown in Fig. 3-14.

A 1% reduction/increase in the year-on-year capacity change leads to cost increases/reductions in the range of 0.21% to 0.37%. This is the shadow cost of the capacity constraints that needs to be reviewed by Nokia should they intend to incorporate such a capacity change. There are two interesting observations here:
CHAPTER 3. OPTIMAL STRUCTURING OF GPD ORGANIZATION.

Figure 3-14: Sensitivity analysis of capacity constraints at Loc $k = 2, 3, 4, 5$

1. the costs reduce in a decreasing manner with more flexibility (higher year on year capacity changes allowed), i.e. it is convex reducing.

2. with increasing flexibility, the number of active capacity change constraints reduces

The above occurrences are functions of the data used. With more flexibility at these locations, the capacity change constraints are active in the earlier periods and hence restructuring and ‘optimal’ capacity transfer to the base and GPD locations occurs earlier. Subsequent capacity transfer does not pay back (work time and coordination time cost save following fixed costs related to hiring, retrenchment, etc.) over the planning period. The above cost sensitivities provide Nokia with an opportunity to make a strategic decision for capacity planning for these locations.

GPD Location $k = 6$

At the GPD location, the capacity change constraint is limited by availability of appropriate manpower, ability to train personnel to required efficiency levels, etc. Thus, though the manpower rates are significantly lower than other locations, it is not possible to increase the capacity as desired. While we worked with a 15% year on year increase in capacity for the base model, we performed sensitivity analysis for 10% and 14% also. The results are shown in Fig. 3-15.

We considered these cases because, as seen in Obs 3, there is a trade-off between lower manpower rates and efficiency challenges when task content is moved to the GPD location. The efficiency improves through learning by doing. However this efficiency increase is hard to achieve if the manpower increases significantly year on year.
3.6. SENSITIVITY ANALYSIS

Figure 3-15: Sensitivity analysis of capacity constraints at GPD Loc $k = 6$ (availability of new manpower with same efficiency levels as that of existing manpower (with experience through repeated doing) is difficult and challenging). Rather the challenge is more to find the appropriate manpower and yet see the target efficiencies (improved through learning) get realized. As seen from the results, difficulties with availing appropriate manpower result in cost increases. However it is not as significant as in the earlier cases of sensitivity analysis. However, Nokia’s key challenge will be to identify and recruit the best and maximum possible manpower at its GPD location.

**Base Location $k = 1$**

Though the capacity change constraints were not active at any time period for the base/home location of Nokia, we felt the need to do sensitivity analysis by incorporating a new constraint. This is driven by the fact that since Nokia is at Finland where availability of additional appropriate manpower is challenged. Since the base location $k = 1$ is the biggest engineering center for Nokia, it has the highest manpower and increasing it by even 1% is challenging. We performed sensitivity analysis using maximum 0%, 1% and 3% capacity changes between years. The results are shown in Fig. 3-16.

Unlike earlier cases, here we observe a concave reducing total cost behavior with respect to relaxation of the capacity constraint value. When compared with the base case where this constraint does not exist, we observe during sensitivity analysis that this constraint is active in all instances where the capacity change is more than the constraint value. Introduction of this constraint has tremendous practical value as hiring of additional appropriate manpower at Nokia’s base location is constrained.
Figure 3-16: Sensitivity analysis with new capacity constraint at Base Loc $k = 1$

### 3.6.2 Learning Rate at GPD Location $k = 6$

Our learning rate calculation at the GPD location was based on actual work time observed by Nokia at time $t = -1$ and -2, and expected work time at $t = 0$. We had extrapolated this learning rate on the work time efficiency factors and compared the expected work time efficiency at $t = 5$ with the existing work time efficiencies at other locations. We had observed that other locations continued to have higher efficiencies (though marginally for some locations), and this supported our earlier assumption that the other locations had ‘non-measurable’ learning by doing benefits. We ran sensitivity analysis for 5%, 10%, -5%, and -10% changes to the learning rate. Our findings are shown in Fig. 3-17.

We observe that if the learning rate is higher than actually calculated for organization design, the realized cost benefits improve. It would also lead to higher allocation of capacity to the GPD location with or without increasing manpower, i.e. higher efficiencies.

### 3.6.3 Manpower Rate at GPD Location $k = 6$

While firms set up and allocate capacity to the GPD locations using existing cost structures, many times the actual cost rates increase at the GPD location and consequently cause the net costs to be higher than originally planned for. Our base organization capacity planning problem had assumed that the costs at all locations would not change over time. We now ran the optimization problem assuming an annual relative inflation of 1%, 5% and 10% respectively at the GPD location (with the manpower rates remaining constant in other locations).
### 3.6. SENSITIVITY ANALYSIS

<table>
<thead>
<tr>
<th>Status Quo</th>
<th>Single Decision</th>
<th>S1</th>
<th>0.000%</th>
<th>0.017%</th>
</tr>
</thead>
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<tr>
<td>0.021%</td>
<td>0.011%</td>
<td>5.89%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.061)%</td>
<td>(0.030)%</td>
<td>7.77%</td>
<td>$2$</td>
<td>0.030%</td>
</tr>
<tr>
<td>(0.055)%</td>
<td>(0.026)%</td>
<td>7.01%</td>
<td>$3$</td>
<td>0.037%</td>
</tr>
<tr>
<td>(0.032)%</td>
<td>(0.018)%</td>
<td>8.55%</td>
<td>$4$</td>
<td>0.024%</td>
</tr>
</tbody>
</table>

Numbers in parentheses () are cost increases, others are cost reductions

**Figure 3-17: Sensitivity Analysis of Learning Rate at GPD Loc $k = 6$**

We observe that the total cost increases with increase in manpower rate at the GPD location. It is interesting to note that the capacity at the GPD location reduces with increasing costs for cases S1, S2, and S3. It is only with case S4 that the capacity increases: however this increase is with new departments being moved to the GPD location rather than increase in the capacity content of the existing departments. As we had observed earlier, the existing departments at the GPD location were those with relatively lower modularity. With case S4, the more modular departments are re-assigned to the GPD location. The significant cost increase in this case is attributable to the fixed costs of change and its under recovery within the planning horizon. The 15% capacity constraint on year over year increase at the GPD location is active for only two time periods and in case C only.

**Uncertainty**

There could be a number of scenarios that Nokia may consider. Our model is general enough to incorporate all of them. We have done sensitivity analysis for certain cases here. Year over year capacity change constraints are driven by strategic and political considerations. In such cases, sensitivity analysis can be used to decide on work assignments for the best value to the firm. However, learning rate and manpower rate changes in the GPD location are more uncertain, and the ability to successively hire appropriate levels of skilled manpower at the GPD location is challenging. While different scenarios can be created and sensitivity analysis run accordingly, it may be advisable to review the task assignment after each period though the decisions may be made for the planning period using an expected value. We observed that when there is an annual manpower rate increase, the capacity change constraint becomes
CHAPTER 3. OPTIMAL STRUCTURING OF GPD ORGANIZATION.

Figure 3-18: Sensitivity Analysis of Manpower Rate increases at GPD Loc k = 6

active for the GPD location only when tasks that are more modular are allowed to be expanded there. Additionally uncertainty in the learning rate also affects the coordination efficiency. These observations imply that Nokia should review to expand departments ranked ModRk1, ModRk2, etc., i.e. the highly modular departments, to the GPD location.

3.7 Robustness of Methodology

In this chapter we developed a methodology, through an empirical example, to structure the global product development organization for a firm engaged in the design and development of complex products. While we have been able to build on the theory developed earlier in the chapter, apply the data observed, and recommend optimization results for the firm to consider, we also need to be confident regarding the robustness of the methodology. Robustness of the optimization tool and the results therein is well established in literature (linear programming gives corner point solution and polynomial time solvable). However, we need to understand the robustness of the data development process. The data used can be separated between that which is measured/available as policy measure by the firm and that which is developed through brainstorming and discussions (qualitative reasoning applied to available quantitative data). In this methodology there are two such pieces of data:

- the work time and coordination time are obtained through discussions with various department personnel who use manpower allocation chart to arrive at the same
3.7. ROBUSTNESS OF METHODOLOGY

- the coordination efficiency uses a four point scale whose respective weights were assigned by curve fitting.

We checked the robustness of the results with respect to each of the above factors. The initial impact of changes in the first piece is on the organization (department) nDSM (Fig. 3-4), and then it flows through, along with the coordination efficiency, onto the organization (department location) nDSM (Fig. 3-7). Changes to the coordination efficiency also flow through the planning horizon.

3.7.1 Coordination time

The coordination time is first quantified on the process-flow DSM (Fig. 3-3) where we obtain the coordination time for each task. After organization mapping, this data transforms into a organization (department) nDSM (Fig. 3-4). For each department, since the manpower allocation is constant, any change to the coordination time is accompanied by corresponding changes to the work time, or change in organization architecture. These changes then impact the organization (department location) nDSM (Fig. 3-7). We had two levels of checks on our earlier data: the program level manpower allocation is used to develop the organization (department) nDSM and the organization (department location) nDSM output was used to compare with the existing manpower distribution.

Our analysis showed that every 10% change in each of the coordination times in the organization (department) nDSM results in 0.66% and 0.6% change in the total actual manpower over all departments and locations and in the 'Status Quo' total costs respectively. The corresponding cost change for 10% and -10% change in the coordination time are, respectively, 1.36% to -1.01% and -0.42% to -0.48% in the various cases (S1, S2, S3, S4). Thus we can say that misinterpretations in the coordination time and work time splits (organization's architecture) result in significantly lower impact on the results.

3.7.2 Coordination efficiency

We looked at coordination efficiencies between locations. We had transferred a rating scale of 1-4 to efficiency factors in the range of 1 to 0.5. We modified the corresponding efficiency factors of 2 and 3 on the scale by 10%. Thus, while the organization (department) nDSM did not change, the organization (department location) nDSM changed. Also the optimization results now had different coordination efficiency factors for all periods. While the 10% increase in efficiency factors led to a cost increase of 1.3% approximately for the S1 case, it led to a cost decrease of approximately 1% in the other cases. In summary we observed that significant changes in quantifying of qualitative data did not have a significant impact on the final results.
3.8 Challenges and Limitations

Though we demonstrated a robust methodology to structure a global product development organization, there exist challenges and limitations. Data requirement for such an exercise is huge and we were fortunate that Nokia has a well streamlined product development process and was forthcoming in developing and providing us the necessary information. Though we were able to develop most data, there was still some data where we were not able to generate the desired visibility, e.g. we used \( \theta_{kk'} \) instead of \( \theta_{ijk'k'} \). Any firm that intends to adopt this methodology needs to have the same level of determination towards data development. Data development challenges, besides differentiating between work time and coordination time, also include determining work and coordination efficiencies, learning rates, etc. which could take a political dimension within the firm.

An assumption input by us was that work time efficiency for a department at any location is independent of the amount of the department capacity assigned. Thus, it is monotonically non-decreasing. However it may be possible that an optimized organization structure may involve capacity allocation reducing significantly over some time periods and then increasing again. In such cases the efficiency factors may actually drop with capacity addition. The efficiency factors would then be a function of the capacity over the various time periods. Then it may not be possible to reduce the mathematical programming formulation to a linear program, raising questions on scalability (polynomial time solutions not guaranteed) and potential duality gap (corner point solution may not exist). In certain cases, if we have a quadratic problem, it may be possible to reduce to polynomial time solutions since the organization (department location) nDSM that we use is square symmetric.

In our model development we have considered capacity in terms of total task time distribution. Many firms use capacity distribution through headcount allocation. In such cases we may have a mixed integer program and the benefits of a linear programming problem may not exist.

3.9 Conclusion

Our results (cost savings) present significant opportunities for Nokia to structure their existing work assignments. Their existing work assignments to the GPD location rank low on modularity, relatively; and with the low coordination efficiency of the various locations with the GPD location, they need to review their work assignment. While political and strategic needs may constrain them from moving work away from some of the established development centers globally, they are also constrained on increasing work assignment at their home location. Hence they need to expand at the GPD center to meet increasing work needs. They need to carefully re-evaluate the tasks that have been offshored to the GPD center and look for opportunities to establish departments that have higher modularity at the GPD center. As shown by the
sensitivity analysis, this approach is also the only way to protect against manpower rate increase (relative) at the GPD location and uncertainty of the learning rate.

Capacity distribution in product development is a challenging proposition. It is further challenged during the development of complex products and particularly when the team involved in development is spread over multiple locations which are separated geographically, culturally, etc. Our approach is an early contribution in this field. We incorporate the architecture of the product under consideration in our modeling approach. Our observations of the results obtained (Obs 3) raise another research question: How does the work time and coordination time of a task change (efficiency differences) when it is transferred to an offshore product development center? How does a firm spread its offshoring efforts between the factors that contribute to these efficiency differences? We discuss this question further in the next chapter.
CHAPTER 3. OPTIMAL STRUCTURING OF GPD ORGANIZATION.
Chapter 4

Effort Distribution in Global Product Development

Chapter Abstract: Offshoring of product development tasks is challenged by the significant coordination requirements between the tasks that have been offshored and those that have not. Academic literature has prescribed modularity, a measure of dis-connectivity, as a possible determinant of the offshore content. However, (a) it is generally not possible, in complex engineered systems, to identify ‘modular’ tasks for offshoring, and (b) other factors (such as competence prevalent at the offshore location) may provide better efficiencies at the offshore location than modularity. In this chapter we develop and analyze a stylized model (two tasks, two locations, two time periods) for a firm seeking to establish a product development center at an offshore location to benefit from cost savings. Our key results show that (a) firms should determine their offshore content to benefit from the existing knowledge base created by the prior offshored content and to create a knowledge base from which subsequent offshoring can benefit (indicating path dependent offshoring) rather than offshoring based solely on modularity; (b) efforts supporting offshoring should prioritize the coordination challenges between tasks at different locations before those between tasks at the offshore location; and (c) in an environment of high volatility of external factors, efforts should be prioritized to enhance the work time and coordination time efficiencies in the first (earliest) period.

4.1 Introduction

While literature on GPD is broad on the subjects of why, where and how firms engage in GPD, it is relatively sparse on ‘what’ the firms should offshore as they engage in GPD. When firms offshore PD tasks seeking competencies, the offshoring content is determined by the competence they seek. When they engage in GPD as a cost saving measure, literature prescribes offshoring content based on modularity, building on the idea that coordination across locations/regions is difficult (Anderson
et al. (2008), Eppinger and Chitkara (2007)). However, for a firm that designs and develops CES, it is very challenging to identify modular content for offshoring. In addition as we observed in chapter 3 (Nokia example), modularity is not the complete answer in determining offshoring content. Literature is also silent on how a firm identifies the (second) next phase offshoring content, and how it is influenced by the previous offshoring choices, nor does it factor in the efficiency gap (takes longer time to complete the PD task) between performing the PD task at the home (existing) location and the new offshore location. Thus, the firm’s managers, besides identifying the offshoring content, also need to be mindful of the efficiency gap.

As a firm decides to offshore PD tasks to a GPD location, it also identifies a set of tasks that it may offshore (based on perceived ease of transfer of responsibility, low interdependence with other tasks, etc.) The firm expends resources, which are limited, to support the offshoring efforts and address the efficiency gaps. Thus these resources need to be appropriately distributed or prioritized amongst the tasks that are to be offshored such that the benefits to the firm are maximized (thus by existing literature it would imply that ‘modular’ tasks should be prioritized). Our interests, in this paper, relate to how this prioritization or distribution of efforts takes place with respect to modularity and the efficiency gap.

We frame our research questions, which address the firm’s dilemma in effort prioritization, as: How does the task completion time change (efficiency differences) when a PD task is transferred to an offshore product development center? How are the firm’s prioritization and distribution of efforts towards the offshored PD tasks affected by the various factors that affect the task completion time? We are particularly interested in situations when the separation (distance, time-zone, culture, etc.) and the efficiency gaps are high. This also aligns with the two complementary observations that we made in chapter 3: (a) work and coordination efficiencies differed across locations, and (b) the transfer of work content to the offshore location was not monotonic with respect to modularity.

We address these questions by developing and analyzing a 2-task, 2-location, 2-time-period model for a firm that is establishing a captive offshore PD center. Our key observation is that a firm should prioritize those tasks for offshoring that develop the competence/knowledge at the offshoring center (rather than offshoring solely based on modularity). This contributes to the learning process of the subsequent tasks that are offshored. However, it also represents a trade-off between the long-term (knowledge development based) and short-term (modularity based) benefits that the firm needs to understand and decide on. Prioritizing offshoring tasks to develop competence/knowledge implies that the offshoring sequence is path-dependent. We also observe that firms should prioritize to manage the coordination required between locations than within locations. In an uncertain environment, firms need to exert substantial upfront efforts to ensure that efficiency differences in work time and coordination time are not significantly affected in an adverse way by the volatility of external factors.
4.2 Model Development

Consider a profit seeking firm with centralized PD operations at home/base location $k = 1$ (e.g. USA, Western Europe). This firm is exploring opportunities for expanding its PD operations globally for cost efficiencies (e.g. a lower manpower cost location in Asia). The firm is involved in the design and development of a single family of products/CES, for which we identify each component-activity combination as a task $n$.

The firm has been able to identify a GPD location $k = 2$ with manpower rate $\ell_k$ such that $\ell_1 >> \ell_2$. The firm expects to benefit from this manpower rate difference. Assume that the firm has identified two tasks $n = 1, 2$ for offshoring. The firm’s options include: do not offshore any task, offshore only one task ($n = 1$ or $n = 2$), offshore the tasks sequentially ($n = 1$ first or $n = 2$ first), or offshore the tasks simultaneously. The firm’s decision would depend on the best value generated amongst the different options, determined through (3.2.3). Our interest in this paper, however, is to identify the factors that contribute to the work time and coordination time efficiency differences as the task is offshored and understand how these factors and the index of modularity affect the distribution/prioritization of efforts of the firm towards offshoring. In this chapter we analyze the cases when the best value option is either when both tasks are offshored simultaneously or sequentially.

We assume that the firm has limited resources, identified through an allocated budget $B$ at $t = 0$. These resources are used in efforts to support offshoring. The effort is spent towards initial setup costs, training, running experiments/dry-runs for familiarity, etc. The effort expended has a direct impact on the efficiency of the work and coordination performed at the offshore location. Thus we have $B_n$ for the respective tasks such that $B \geq B_1 + B_2$. The value and sensitivity of $B_n$ is an indication of the prioritization of efforts that the firm undertakes. Our research question requires us to understand the impact of various factors that influence the work time and coordination time at the offshore location on the optimal efforts exerted, $B_1^*$ and $B_2^*$. We assume that the effort is expended on a task only once, and in the time period before it starts performing the task at GPD location $k = 2$ (we briefly outline the case when the effort is expended over two periods in the Appendix). We also assume that the complete task is offshored, i.e. $A_{nkt} \in \{0,1\}$.

In the next section we determine the dynamics of work time and coordination time (the constituents of task time) as the two tasks are offshored from the home location $k = 1$ to the GPD location $k = 2$. We incorporate the factors that influence work time and coordination time, e.g. how effort allocation acts, how does learning by repeated doing impact work time and coordination time, etc. Effort, corresponding to budget $B$ is expended during period $t = 0$ (or $t = 1$ for sequential offshoring). The outcome of this effort is observed during $t = 1$ and carried over to $t = 2$ when some other factors are also observed. Our modeling approach has similarities with Loch and Kavadias (2002).
4.2.1 Dynamics of Work Time

Assume that the tasks \( n = 1, 2 \) have respective work time \( w_1 \) and \( w_2 \) and coordination time \( c \) between them at \( k = 1 \). The coordination time is required to ensure successful execution of the task and includes receiving and providing information related to the task. We assume that these tasks do not have coordination requirements with any other task (which are at the home location \( k = 1 \)): \textit{we will relax this assumption later.}

When the tasks are offshored to \( k = 2 \), the work time \( w_n \) changes to \( w_n \cdot g_n \) (Fig. 4-1), \( g_n \) is the offshoring penalty incurred (\( g_n > 1 \)) (Herbsleb and Mockus (2003)). \( n \) is a new task at the GPD location, and though there is a manpower rate reduction (\( \ell_2 << \ell_1 \)), the time taken to complete the task increases due to novelty, available knowledge of the task, familiarity with the task, etc. \( g_n \) is a function of the GPD location, the talent available there, and the ability of the firm to take advantage of knowledge spillover at the GPD location. If \( g_n \leq 1 \), the problem would be trivial with both cost rate and work time reducing. Similarly if \( g_n \approx 1 \) and \( \ell_2 << \ell_1 \) the problem may be very trivial. We will assume that \( g_n \) is significantly high for a tradeoff (\( g_n \) vs. \( \ell_1 - \ell_2 \)) to exist.

The respective distributions \( B_n \) have an impact on the work time as \( f_n(B_n) \). This effort can be termed as training/familiarity before task execution starts. Further, \( 0 \leq f_n(B_n) \leq 1 \) with \( f_n(0) = 1 \), i.e. when there is no investment \( f_n \) has unity value. Thus \( f_n(B_n) \) is reducing in \( B_n \), i.e. \( f_n'(B_n) < 0 \) such that the actual work time at \( t = 1 \) for task \( n \) at \( k = 2 \) is \( w_n \cdot g_n \cdot f_n(B_n) \) (Fig. 4-1). The effort exerted (training before the job) mitigates the adverse effect of \( g_n \) of increasing the work time. We also assume that \( f_n(B_n) \) is convex and twice differentiable, i.e. \( f_n''(B_n) \geq 0 \). Concave reducing \( f_n(B_n) \) would imply increasing returns to the efforts applied. Then with high effort \( B_n \), the actual work time can reduce to \( w_n \) (thus quicker to perform task at GPD location at a lower manpower rate, and so not an interesting proposition), or with still higher effort we may be able to reduce the work time to 0 (unlikely to happen). Concavity may exist during the initial efforts but would not be sustainable as the effort exerted increases. Thus, \( f_n(B_n) \) is either convex or S-shaped with an initial concave part (some minimum effort has to be exerted before benefits are observable) before moving into the convex region, i.e. with incremental effort, the returns will tend to be diminishing. While all our model analysis is based on convex reducing \( f_n(B_n) \), we also consider the S-shaped behavior in the proof of Result 1.

In the next period \( t = 2 \), the offshore location performs the task for the 2nd time and hence experiences a learning effect \( r_n \) (learning by doing repeatedly (Argote (1999), Boone and Ganeshan (2001))). In parallel, there are some effects observed from having performed the other task \((-n)\) at the GPD location during \( t = 1 \), \( \mu_{-n} \) (learning by doing something else (Schilling et al. (2003))). Learning by doing something else is dependent on the ability of the firm’s offshore facility’s ability (absorptive capacity: Cohen and Levinthal (1990), Kogut and Zander (1992)) to assimilate the learning
obtained from a related task that is also being done at the offshore location so as to enhance the learning rate (Schilling et al. (2003)). As argued in the previous chapter, product development is a set of information processing tasks (Brown and Eisenhardt (1995)). Thus engineers compare the different information tasks that they are involved in and create an abstract, based on the commonalities (Schilling et al. (2003)), that they are then able to transfer between the tasks, enhancing the learning rate. This learning is implicit. We introduce this enhancement in the learning rate as $\mu_n$ through $2^{-(r_n + \mu_n)}$. The learning by doing the other task helps the GPD location to learn task $n$ faster by doing along with a related task. Thus, the time required to perform the task is $w_n g_n f_n(B_n) \cdot 2^{-(r_n + \mu_n)}$ (Fig. 4-1).

4.2.2 Dynamics of Coordination Time

The coordination time $c$ also changes similar to work time. Coordination time is the maximum of the time required for coordination among the participating tasks, i.e. the coordination time of the task which requires more coordination time. Note: we are assuming that the effort $B_n$ is exerted for the task and is not separable between the effort to improve work time efficiency and the effort to improve coordination time efficiency.

Thus, for $t = 1$, the coordination time is $c g_c \max_n(f_n(B_n))$, where $g_c$ is similar to $g_n$, i.e. the increase in coordination time when both tasks are moved to the GPD location ($g_c > 1$ due to the ‘newness’ of the task at the GPD location $k = 2$).
The factor \( \max_n(f_n(B_n)) \) is used since coordination time is determined as \( c_{ab} = \max(c_a, c_b) \), where \( c_{ab} \) is the coordination required between two tasks \( a \) and \( b \), \( c_a \) and \( c_b \) are the respective coordination time requirements of tasks \( a \) and \( b \), and \( f_n(B_n) \) is reducing in \( B_n \). We observe that the effort \( B_n \) being exerted on the task \( n \) helps to improve its deliverables (work and coordination time efficiencies). It helps the respective tasks to recognize their interactions with and dependencies on the other task, leading to better coordination and reduction in coordination time.

Similarly, at \( t = 2 \), the coordination time is \( c_g \cdot \max_n(2^{-(r_{nc}+\mu_{-nc})} \cdot f_n(B_n)) \). Besides the impact of the effort applied towards supporting the setting up of task \( n \) at the GPD location \( B_n \), the tasks also learn by coordinating again, i.e. they learn to coordinate 'better'. They recognize their mutual dependencies better and are able to improve on the coordination time. \( r_{nc} \) represents the respective coordination time learning rates of task \( n \). Similar to work time, there is also a learning rate increment by doing the other task at the offshore location (both tasks are being done at the offshore location). We assume that \( r_{1c} = r_{2c} = r_c \) and differential learning rates between the two tasks are captured through \( \mu_1 \) and \( \mu_2 \) respectively, i.e. we consider \( \mu_{-nc} = \mu_n \).

### 4.2.3 Problem Formulation

We collate the terms corresponding to the dynamics of work time and coordination time to determine the total cost of the case when both the tasks \( n = 1, 2 \) are offshored simultaneously as follows:

\[
x = B + e^{-\beta} \cdot (\ell_2 \cdot \sum_n w_n \cdot g_n \cdot f_n(B_n) + 2 \cdot \ell_2 \cdot c_g \cdot c_g \cdot \max_n(f_n(B_n))) + e^{-2\beta} \cdot (\ell_2 \cdot \sum_n w_n \cdot g_n \cdot 2^{-(r_{nc}+\mu_{-nc})} \cdot f_n(B_n) + 2 \cdot \ell_2 \cdot c_g \cdot c_g \cdot \max_n(2^{-(r_{nc}+\mu_{-nc})} \cdot f_n(B_n)))
\]

Thus, the problem formulation is now

\[
\begin{align*}
\text{Min} & \quad x \\
\text{subject to} & \quad \sum_n B_n \leq B, \quad n = 1, 2
\end{align*}
\]

Solving (4.2.2) will give the minimum cost that will be incurred (4.2.1) when the two tasks are offshored simultaneously and the optimal distribution of efforts (corresponding to budgets \( B_n^* \)). Similar formulations can also be developed for the cases when neither of the tasks is offshored, when only one task is offshored or the tasks are offshored sequentially.
4.3. MODEL ANALYSIS

Sequential Offshoring:

There will be some differences in the dynamics of work time and coordination time changes when the tasks are offshored sequentially. Consider the case where the firm offshores task $n = 1$ at time $t = 1$ and follows it with task $n = 2$ at $t = 2$.

The work time for task $n = 1$ will evolve as in the simultaneous case for $t = 1$ but the benefits of learning by doing something else, i.e. $\mu_2$, will be affected by a factor $\delta_1$ ($\delta_1 > 0$) since task $n = 2$ is performed at the home location $k = 1$ at $t = 1$. $\delta_1$ is influenced by the coordination requirement $c$ between the tasks. $\frac{d\delta_1}{dc} > 0$, i.e. with higher coordination the learning rate for task $n = 1$ at the GPD location will be higher, albeit limited by the absorptive capacity (Cohen and Levinthal (1990)) at the GPD location. Similarly the coordination time $c$ now increases by $g_{c1}$ due to task $n = 1$ at the GPD location and $n = 2$ at the home location ($g_{c1.1}$). This increase is partially mitigated by the impact of the effort exerted $f_1(B_1)$. We assume that since the tasks had been performed at the home location $k = 1$ for a long time, the learning between successive time periods is insignificant.

Similarly at time $t = 2$, $n = 2$ is also offshored. The impact of the effort exerted $B_2$ is affected by a factor $\nu$ ($\nu > 0, \nu \leq 1$). Thus the increase in work time by $g_2$ is mitigated by a factor $f_2(\nu.B_2)$. However, though the task is being done for the first time at the GPD location, there is a learning effect from having done task $n = 1$ during $t = 1$ and this is experienced as $(1 + \varepsilon)^{-\delta_2\mu_1}$ where $\varepsilon > 0$ (to capture the learning effect) and $\varepsilon \to 0$, and $\delta_2 > 0$ is similar to $\delta_1$ described earlier. Collating the terms, we obtain the total cost for the case of offshoring $n = 1$ in the first period and $n = 2$ in the next period as follows:

$$x' = B_1 + e^{-\beta}(B_2 + \ell_2.w_1.g_1.f_1(B_1) + \ell_1.w_2 + (\ell_1 + \ell_2).c.g_{c1}.f_1(B_1))$$

$$+ e^{-2\beta}.(\ell_2.w_1.g_1.f_1(B_1).2^{-(r_1+\delta_1}\mu_2) + \ell_2.w_2.g_2.f_2(\nu.B_2).(1 + \varepsilon)^{-\delta_2\mu_1} + 2.\ell_2.c.g_c.max(2^{-(r_1+\delta_1}\mu_2).f_1(B_1),(1 + \varepsilon)^{-\delta_2\mu_1}.f_2(\nu.B_2)))$$

Thus, the problem formulation for the sequential offshoring case is

$$\text{Min} \quad x'$$

$$\text{subject to} \quad B_1 + e^{-\beta}.B_2 \leq B$$

4.3 Model Analysis

In this section, we solve the formulations developed in the previous section, and then follow with comparative statics analysis to determine the effort prioritization during offshoring.
4.3.1 Simultaneous Offshoring

To solve the non-linear optimization problem (4.2.2) we start by forming the Lagrangean:

\[ L(B_n, v) = x + v(B - \sum_n B_n) \quad \text{for} \quad n = 1, 2 \quad (4.3.1) \]

With two decision variables, we follow the Kuhn-Tucker conditions. However since we are considering effort application once for any task and given the convex (or concave-convex S-shaped) reducing behavior of \( f_n(B_n) \), any effort applied would result in an improvement to the work time and coordination time. Our model is developed for a profit seeking firm that is looking to reduce costs by offshoring product development tasks. We assume that the firm is resource constrained, i.e. the available effort (hence budget \( B \)) is such that if budget \( B_1 \) \((B_1 > B)\) were available, it would reduce the total cost further. Hence, for optimal distribution of the efforts, we assume that \( B = \sum_n B_n \). So we now have a single decision variable. Without loss of generality, we assume

\[ \max_n (f_n(B_n)) = f_1(B_1) \quad \text{and} \quad \max_n (2^{-(r_c+\mu_n)} f_n(B_n)) = 2^{-(r_c+\mu_2)} f_1(B_1) \quad \text{where} \quad 2^{-(r_1+\mu_2)} = 2^{-(r_c+\mu_2)} \]

Our analysis shows that using \( \max_n (2^{-(r_c+\mu_n)} f_n(B_n)) = 2^{-(r_c+\mu_1)} f_2(B_2) \), i.e. different tasks in different periods for the max function, does not affect the comparative statics results.

Incorporating the above assumptions in (4.2.1), (4.2.2) and (4.3.1), we obtain:

\[ L(B_1) = x_1 \quad \text{where} \quad x_1 = B + e^{-\beta}(l_2.w_1.g_1.f_1(B_1) + w_2.g_2.f_2(B - B_1)) \]

\[ + 2.l_2.c.g.c.f_1(B_1)) + e^{-2\beta}(l_2.w_1.g_1.2^{-(r_1+\mu_2)} f_1(B_1) \]

\[ + l_2.w_2.g_2.2^{-(r_2+\mu_1)} f_2(B - B_1) + 2.l_2.c.g.c.2^{-(r_c+\mu_2)} f_1(B_1)) \]

The above Lagrangean is solved for minimization using the first order conditions. Second order conditions prove that the solutions to the first order conditions give the minimum value to the Lagrangean. All proofs are outlined in the Appendix. We obtain solutions as outlined in Result 1. The effort allocation is a ratio of the marginal returns of the efforts expended (similar to Loch and Kavadias (2002)).

**Result 1:** The distribution of effort is given by (if a solution exists):

\[ \frac{f_1'(B_1^*)}{f_2'(B - B_1^*)} = \frac{w_2.g_2.(1 + e^{-\beta}.2^{-(r_2+\mu_1)})}{w_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\mu_2)}) + 2.c.g.c.(1 + e^{-\beta}.2^{-(r_c+\mu_1)})} \quad (4.3.4) \]

If a solution does not exist, all efforts are prioritized to the task that ensures the least total cost.
4.3. MODEL ANALYSIS

The above solution (4.3.4) is a single equation in a single variable. Numerical methods can be used to solve such problems. We observe that the distribution of efforts is a ratio of the marginal effects of the efforts exerted (similar to Loch and Kavadias (2002)). If a solution does not exist or the minimization conditions are not satisfied, all efforts are applied to the task which gives better benefits to the efforts applied. The other task may also be offshored in this case but without any support in terms of training, familiarization, etc.

While we solved for optimality, our interest lies in understanding how the optimal effort allocation changes with the various factors that we have identified. We use comparative statics to establish the relationships between the optimal effort allocations and these factors. Comparative statics uses the envelope theorem on optimality conditions to generate a set of simultaneous equations which are solved to determine the respective sensitivities.

Using the definition of index of modularity (3.2.2), we define the respective indices of modularity for task \( n \) \((n = 1, 2)\), as \( \frac{1}{\eta_n} = \frac{w_n}{w_n + c} \). Thus we get \( \frac{1}{\eta_1} = \frac{w_1}{w_1 + c}, \frac{1}{\eta_2} = \frac{w_2}{w_2 + c} \), and \( c = (\eta_1 - 1)w_1 \).

**Proposition 1:** The optimal effort allocations (corresponding to \( B^*_1 \)), when a solution (4.3.4) exists:

a) \( B^*_1 \) decreases with modularity \((1/\eta_1)\) of the task.

b) \( B^*_1 \) increases when the other task’s learning rate can benefit from task \( n = 1 \) being done at the offshore location simultaneously \((\mu_1)\), but decreases when the task \( n = 1 \) can benefit from the other task being performed at the offshore location \((\mu_2)\).

c) \( B^*_1 \) decreases if the task’s work time and coordination time learning rates \((r_1, r_c)\) are high, i.e. rely on learning rate benefits in subsequent periods.

d) \( B^*_1 \) increases with the offshoring penalty of the work time \((g_1)\) and/or of the coordination time \((g_c)\) of the task.

The first finding highlights that for optimal conditions, the effort allocation does not increase with modularity. This may appear contrary to literature which prescribes that preference should be given to modular tasks (extending Sanchez and Mahoney (1996), Baldwin and Clark (2000), Langlois (2002) to imply tasks with higher modularity). However, in our 2 task scenario, allocating upfront efforts (training) to the more modularity task may help its work time and coordination time but the actual coordination time spent is the maximum of the coordination time required by the two tasks. So if higher effort is allocated to the more modular task, the other task (with relatively higher coordination time in its task time) does not see related improvements in its coordination time. In summary, the effort spent on the modular task is not appropriately ‘rewarded’ through improvements to the total cost/total time spent over all tasks in the GPD center.

The second finding indicates that it is prudent to invest in tasks which help in
improving the efficiencies of the other task, i.e. by applying effort to one task, the
effects are also felt in the other related task (Schilling et al. (2003)) such that the
other task improves its learning ability, leading to reduction in work time and hence
related costs. However this effort need not be high if there are learning benefits from
investing in the other task. This is an interesting observation since it would mean that
the priority should lie on identifying and allocating effort to those tasks for offshoring
that will aid other tasks as they are offshored but the effort need not necessarily give
the best benefit for the task itself. This is a key observation that we discuss further
in section 4.5.

The improvements through learning rate and through initial efforts (training, fa-
miliarization, etc.) lead to long-term and short-term benefits respectively. Thus, for
tasks with high work time or coordination time learning rates, higher efforts need not
be expended as improvements are obtained through repeated doing. On the other
hand, if the work time learning rate of the other task is high, then efforts need to be
prioritized towards the base task's GPD efforts because as the other task improves in
work time, its related benefits to the coordination time will not be obtained unless the
base task is also able to improve accordingly (coordination time required is maximum
of coordination time requirement of the two tasks).

The fourth finding on the proposition states that efforts should be prioritized for
tasks which have high offshoring penalty, either work time or coordination time. This
is required to reduce the resultant extra time and cost from offshoring.

4.3.2 Sequential Offshoring

We solve the equations developed for the sequential offshoring case (4.2.3 and
(4.2.4)) by forming the Lagrangian as in the earlier subsection (4.3.1) and then using
the first and second order conditions.

Result 2: The distribution of effort is given by (if a solution exists): 

\[
\frac{f'_1(B_1^*)}{f'_2(\nu, e^{\beta}(B - B_1^*))} = \frac{\ell_2 w_2 g_2 \nu (1 + e)^{-\delta_2 \mu_1}}{\ell_2 w_1 g_1 + (\ell_1 + \ell_2) c g_c + e^{-\beta} (\ell_2 w_1 g_1 2^{-(r_1 + \delta_1 \mu_2)} + 2 \ell_2 c g_c 2^{-(r_1 + \delta_1 \mu_2)})}
\]

If a solution does not exist, all efforts are prioritized to the task that ensures the least
total cost.

As in the simultaneous case, the solution for the sequential offshoring case (4.3.5)
is also a single equation in a single variable and is ratio of the marginal effects of the
efforts exerted. We apply comparative statics, but unlike the simultaneous case, we
need to observe for impact on $B_1^*$ and $B_2^*$, i.e. the efforts applied for the first task
and the efforts applied for the second task.

**Proposition 2:** The optimal effort allocations (corresponding to \( B_1^* \) for the first period offshoring and \( B_2^* \) for the second period offshoring), when a solution ((4.3.5) or (B.3.2)) exists:

a) \( B_1^* \) decreases with modularity \( (1/\eta_1) \) of the task, but \( B_2^* \) increases with modularity \( (1/\eta_2) \).

b) Both \( B_1^* \) and \( B_2^* \) decrease with the benefit that the respective tasks obtain by performing the other task at the offshore location, but increase when by performing them the other task benefits through enhanced learning rate.

c) \( B_1^* \) decreases if the task’s work time and coordination time learning rates \( (r_1, r_c) \) are high, i.e. rely on learning rate benefits in subsequent periods.

d) \( B_1^* \) increases with the offshoring penalty of the work time \( (g_1) \) and of the coordination time \( (g_1, g_c) \) of the task, and while \( B_2^* \) increases with the offshoring penalty of the work time \( (g_2) \), it decreases with the second period offshoring penalty \( (g_c) \).

Statement a) of Proposition 2 says that the second period effort is increasing in the modularity of the task and statement d) outlines that the second period effort does not increase with the coordination time penalty (unlike the first period effort). Thus it is evident that the efforts towards the second period offshoring are directed towards improving the work time efficiency at the offshore location, and in benefiting from the learning rate from the first period offshoring. Improvements in the coordination time between the tasks arise more from the efforts input to support the first period offshoring and the learning (by repeated coordination and by learning from the work time).

### 4.3.3 Interactions with Home Location

Now assume that the two tasks, besides coordination needs amongst themselves, also have coordination needs with other tasks of the CES which are constrained to the home location. So the two tasks \( n = 1 \) and \( n = 2 \), as earlier, have respective work time \( w_1 \) and \( w_2 \), coordination time \( c \) amongst them, and also have respective coordination time \( c_1 \) and \( c_2 \) with the other tasks. The respective indices of modularity are now given as \( \frac{1}{\eta_n} = \frac{w_n}{w_n + c + c_n} \). We also identify another measure of modularity, i.e. index of within modularity, such that \( \frac{1}{\eta_n} = \frac{w_n}{w_n + c} \). Thus, \( \frac{1}{\eta_n} \rightarrow \frac{1}{\eta_0} \) as \( c_n \rightarrow 0 \) and \( \frac{1}{\eta_n} \leq \frac{1}{\eta_0} \).

Similar to \( c = (\eta_{n_0} - 1)w_n \), we get from the definitions \( c_n = (\eta_n - \eta_{n_0})w_n \).

The dynamics of work time and coordination time when the tasks are offshored simultaneously is shown in Table 4.1. \( g_{cm} \), \( (n = 1, 2) \) is similar to the offshoring penalty for coordination time \( g_c \) defined earlier, but instead corresponds to the coordination time between task \( n \) and the other tasks at the home location. \( r_{cm} \) corresponds to the learning rate of coordination time between task \( n \) and the other tasks at the home location. Parameters \( h_1 \) and \( h_2 \) reflect that the learning rate benefits by doing the
other task is not the same as in the case of work time and coordination time between the offshored tasks, i.e. \( h_n < 1 \).

Following the earlier steps, we get for the simultaneous offshoring option:

**Proposition 3:** The optimal allocation \( B_1^* \), when both tasks are offshored together (simultaneously) and there exists coordination needs with other tasks that are constrained to the home location:

- a) \( B_1^* \) decreases with modularity \((1/\eta_1)\) of the task, but increases with the within modularity \((1/\eta_{10})\) of the task.
- b) \( B_1^* \) increases with the benefit that the other task’s learning rate \((\mu_1)\) can get by doing task \( n = 1 \) simultaneously but decreases when its own learning rate can benefit from performing the other task simultaneously \((\mu_2)\).

Similarly we proceed for the option of sequential offshoring. The changes in the work time and coordination time are shown in Table 4.2 (assuming that task \( n = 1 \) is offshored first and \( n = 2 \) follows in the next time period). \( g_{cb} \) is the coordination efficiency when task \( n = 1 \) is at the GPD location and \( n = 2 \) is at the home location. Since the task \( n = 1 \) has already been performed at the GPD location before \( n = 2 \) is introduced, there is a transfer of learning effect which is reflected in the work time of \( n = 2 \) as \((1 + \epsilon)^{-(\gamma_2 + \mu_1)}\) and due to this, the full benefits of the efforts towards introduction of \( n = 2 \) are not realized. Hence we have \( f_2(k.B_2) \), where \( k < 1 \). \( \delta < 1 \) in the work time and coordination time of \( n = 1 \) reflects that though \( n = 2 \) is introduced at the GPD location at \( t = 2 \), \( n = 1 \) has had coordination with \( n = 2 \) when it was at the home location and this has benefited the learning rate.

Following the earlier steps, we get for the sequential offshoring option:

**Proposition 4:** The optimal allocation \( B_1^* \) (the first period offshoring) and \( B_2^* \) (the second period offshoring), when the tasks are offshored sequentially and there exists coordination needs with other tasks that are constrained to the home location:
4.3. MODEL ANALYSIS

Table 4.2: Sequential offshoring with coordination with ‘home based’ tasks

<table>
<thead>
<tr>
<th>Time Description</th>
<th>$t = 1$</th>
<th>$t = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 1$ work</td>
<td>$\ell_2.w_1.g_1.f_1(B_1)$</td>
<td>$\ell_2.w_1.g_1.f_1(B_1)$</td>
</tr>
<tr>
<td></td>
<td>$\cdot 2^{-(r_1+\ell_{12})}$</td>
<td>$\cdot 2^{-(r_1+\ell_{12})}$</td>
</tr>
<tr>
<td>$n = 2$ work</td>
<td>$\ell_1.w_2$</td>
<td>$\ell_2.w_2.g_2.(1+\epsilon)^{-(r_2+\mu_1)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\cdot 2^{-(r_2+\mu_2)}$</td>
</tr>
<tr>
<td>coord. b/w $n = 1$ and $n = 2$</td>
<td>$(\ell_1 + \ell_2).c.g_2.f_1(B_1)$</td>
<td>$2.\ell_2.c.g_2.f_1(B_1)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\cdot 2^{-(r_2+\mu_2)}$</td>
</tr>
<tr>
<td>coord. b/w $n = 1$ and other tasks</td>
<td>$(\ell_1 + \ell_2).c_1.g_1.f_1(B_1)$</td>
<td>$(\ell_1 + \ell_2).c_1.g_1.f_1(B_1)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\cdot 2^{-(r_1+\mu_2)}$</td>
</tr>
<tr>
<td>coord. b/w $n = 2$ and other tasks</td>
<td>$2.\ell_1.c_2$</td>
<td>$(\ell_1 + \ell_2).c_2.g_2.f_2(k.B_2)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\cdot (1+\epsilon)^{-(r_2+\mu_2)}$</td>
</tr>
</tbody>
</table>

a) Both $B_1^*$ and $B_2^*$ decrease with modularity ($1/\eta$) of the task, but increase with the within modularity ($1/\eta_{n0}$) of the task.
b) Both $B_1^*$ and $B_2^*$ increase with the benefit that the other task’s learning rate ($\mu_1$) can get by doing task $n = 1$ simultaneously but decrease when its own learning rate can benefit from performing the other task simultaneously ($\mu_2$).

Modularity Within or Total Modularity: We collate the findings of Propositions 1 through 4 in Table 4.3. The top row (from Proposition 1 and Proposition 2) posits

Table 4.3: Comparative Statics of Optimal Effort to Within and Total Modularity

<table>
<thead>
<tr>
<th>Coordination</th>
<th>Simultaneous Offshoring</th>
<th>Sequential Offshoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only amongst $n = 1$ and $n = 2$</td>
<td>$\frac{dB_{1}}{d1/\eta_1} &lt; 0$</td>
<td>$\frac{dB_{2}}{d1/\eta_2} &gt; 0$</td>
</tr>
<tr>
<td>Coordination amongst $n = 1$, $n = 2$ and home loc. tasks</td>
<td>$\frac{dB_{1}}{d1/\eta_1} &lt; 0$</td>
<td>$\frac{dB_{1}}{d1/\eta_{10}} &gt; 0$</td>
</tr>
<tr>
<td></td>
<td>$\frac{dB_{2}}{d1/\eta_2} &lt; 0$</td>
<td>$\frac{dB_{2}}{d1/\eta_{20}} &gt; 0$</td>
</tr>
</tbody>
</table>

that the offshoring efforts are directed towards improving the coordination between the tasks, and during sequential offshoring, the efforts for the second period offshoring are directed towards improving this offshoring content’s work time efficiencies. In contrast, Proposition 3 and Proposition 4 provide an interesting perspective. They say that the optimal effort to support offshoring is always reducing in the index of total modularity but is increasing in the index of within modularity. Higher within modularity implies lower coordination between the tasks $n = 1$ and $n = 2$ that have been offshored, while lower total modularity implies more coordination with the tasks that are constrained to the home location. Thus these propositions posit that efforts
should applied to improve the coordination between home and GPD locations rather than within the GPD location.

We interpret these results to conclude that, when the offshore content has interactions with tasks that are constrained such that they cannot be offshored, the efforts that support GPD are allocated to improve the efficiencies of work time at the GPD location and the coordination needs between locations.

4.4 Uncertainty and Risk Averse Firm

In the previous section we analyzed the prioritization of efforts for the deterministic case. However, in many cases, all information may not available with certainty. With uncertainty there arises the possibility that the firm may be either risk neutral or risk averse. Our earlier formulations and results correspond to both the risk neutral and risk averse cases, with expectation taken for the parameters that are uncertain. However a risk averse firm would also consider the variability of the uncertain parameters. If utility of a firm that incurs a cost of $x$ is given by $U(x)$, then for a risk averse firm $U'(x) < 0$ and $U''(x) < 0$ (concave utility function of risk averse firm (Mas-Collel et al. (1995))). We now review the sensitivity of effort prioritization in the presence of uncertainty.

4.4.1 Uncertainty in GPD Location’s Learning Capability

As discussed earlier, the firm exerts efforts to support realization of lower work time and coordination time (better efficiencies) from its PD center at the GPD location. However, in addition to the firm’s efforts, the existing capability of the GPD location and the prevalent absorptive capacity (Cohen and Levinthal (1990)), which represent the capability of the GPD location, also play a key role. Often information regarding the capability of the GPD location is uncertain (though there could exist some information about how related tasks of other similar firms are being performed at that location). Thus the firm’s knowledge of the work time and coordination time when engineering development tasks are offshored is estimated with some distribution. Here we analyze the impact of the variability of the learning rates. There is limited literature on dealing with learning curve uncertainty. It has been modeled for production by Mazzola and McCardle (1997), who have also suggested a Bayesian updating approach to determine optimal production quantity during such uncertainty (Mazzola and McCardle (1996)). However our modeling approach has used the learning rate as a contributor to determine offshoring content, and there does not appear to be any literature that addresses uncertainty in such circumstances.

The difference in work time between $t = 1$ and $t = 2$ is due to the learning effects (by doing and by doing something else), and this difference is $E[2^{-(r_1 + \mu_2)}]$. We assume that the firm has knowledge that $r_1 + \mu_2 \sim N(\bar{r}_1 + \bar{\mu}_2, \sigma_{r_1,\mu_2}^2)$, where $\sigma_{r_1,\mu_2}^2$ represents the variance-covariance matrix of the learning rate by doing and learning
rate by doing something else (hereafter referred to as the variability of the work time or coordination time learning rate).

We incorporate these uncertainty changes to the various terms in (4.2.1) and (4.2.3). We then transform the terms related to learning impact as:

\[ E[2^{-(r_1 + \mu_2)}] = E[e^{-(r_1 + \mu_2).ln2}] = e^{-ln2.(r_1 + \mu_2)} + \frac{1}{2}.(ln2)^2.\sigma^2_{\mu_1,\mu_2} \]  \hspace{1cm} (4.4.1)

Following the solution and analysis methods followed in earlier proofs, we obtain the following proposition:

**Proposition 5: Uncertain learning rate at GPD location:** The optimal allocation \( B_1^* \), when both tasks are offshored simultaneously, is increasing with the variability of the work time learning rate \( \sigma_{\mu_1,\mu_2} \) and the coordination time learning rate \( \sigma_{\mu_2} \). The results are same when the tasks are offshored sequentially, for both the first period optimal allocation \( B_1^* \) and the second period optimal allocation \( B_2^* \).

The above proposition shows that the risk-averse firm would react to uncertainty in the learning rate by increasing the effort allocation as the learning rate variability increases. These results resonate with the findings of Carrillo and Gaimon (2004) who derived analytically that managers invest in the workers' capabilities when uncertainties in achieving the desired production capacity outputs are high. Variability in the learning rate corresponds to the limited knowledge about the GPD location at the time of effort allocation and the novelty of the task to the GPD location. Thus we can conclude that with higher variability, the firm will push for higher efforts (budgets) to be allocated such that \( f_B(B_1) \) reduces and the impact of (adverse) volatility of the learning rates on the firm's utility function is minimized.

Similarly when the capability at the GPD location is uncertain, the \( t = 1 \) work time, after applying effort \( B_1 \) at \( t = 0 \), at the GPD location is \( w_1.E[f_1(\xi_1, B_1)] \), in contrast to \( w_1.g_1.f_1(B_1) \) when full information is available (refer Fig (4-1)). Similar to \( f(B) \), we have \( E[f'_B(\xi, B)] < 0 \) and \( E[f''_B(\xi, B)] > 0 \), where \( E[f'_B(\xi, B)] = \frac{dE[f_B(\xi, B)]}{dB} \) and \( E[f''_B(\xi, B)] = \frac{d^2E[f_B(\xi, B)]}{dB^2} \). Applying an explicit form for this uncertainty and following the same step as the proof of Proposition 5, we observe that the risk-averse firm will prioritize higher efforts when the capability of the GPD location is uncertain.

### 4.4.2 Innovative systems

Our earlier results and observations build on the premise that the index of modularity of the tasks remains constant (steady architecture). However this may not be case when the firm is developing innovative products, i.e. the development effort required for successive products changes, thus affecting the index of modularity. We will assume, for simplicity, that the coordination time changes with successive generations.
of the CES that the firm is designing and developing, leading to changes in the index of modularity. We capture this through $\eta_n = \frac{w_n + c}{u_n}$ with $\eta_n \sim N(\eta_n^*, \sigma_{\eta_n}^2)$. In such cases, when offshored, it is likely that the learning rates may also vary due to the constant ‘newness’ of the job. Since we observed the effort prioritization with respect to the learning rate factors in the earlier sub-section, we will consider it to be constant here.

As shown by Merton (1969) and Loch and Kavadias (2002), we assume that the utility function is negative exponential with constant absolute risk aversion $\alpha$, i.e. $U(x) = \frac{1}{\alpha} - \frac{1}{\alpha}e^{-ax}$. We then use the earlier transformation (4.4.1) to get $E[U(x)] = \frac{1}{\alpha} - \frac{1}{\alpha}e^{-aE[x]} + \frac{1}{2}\alpha^2 \sigma_x^2$. We assume that $E[x] = \frac{1}{2}\alpha \sigma_x > 0$ to ensure that the firm always has positive utility. On solving the respective Lagrangeans and applying the envelope theorem, we obtain the following proposition:

**Proposition 6:** Innovative complex engineered systems: The optimal allocation $B_1^*$, when both tasks are offshored simultaneously, is increasing in the variability of the index of modularity $1/\sigma_{\eta_1}^2$. If the tasks are offshored sequentially, the first period optimal allocation $B_1^*$ increases in the variability of the index of modularity $1/\sigma_{\eta_1}^2$, but the second period optimal allocation $B_2^*$ decreases in the variability of the index of modularity $1/\sigma_{\eta_2}^2$.

Since the task time is uncertain for innovative CES, there is an apprehension that the offshore location may not be able to manage the uniqueness in successive generations of the CES. So if the expected variability is high, it is prudent to support offshoring with high efforts such that the knowledge gained by the offshore location can handle the CES changes and the efficiency differences between the home and the GPD location are minimized over successive CES generations. When the tasks are offshored sequentially, the same apprehensions remain for the task that is offshored first and hence the same approach. Since the variability is on account of the coordination requirements, most efforts to manage the same have been applied to the first period offshoring and need not be repeated completely for the second period offshoring. So the second period allocation is decreasing with the variability of the index of modularity.

Observing Proposition 1, Proposition 2 and Proposition 6 together, we see that the first period optimal allocation $B_1^*$ is decreasing in modularity $1/\eta_1$ but increasing in the variability of modularity $1/\sigma_{\eta_1}^2$. Similarly the second period allocation is increasing in modularity $1/\eta_2$ but decreasing in the variability of modularity $1/\sigma_{\eta_2}^2$. Thus we can conclude effort allocation recognizes the challenges of coordination and hence the early effort aims at managing the coordination challenges and the later efforts at managing the work time efficiencies of the subsequent offshoring content.
4.4. UNCERTAINTY AND RISK AVERSE FIRM

4.4.3 Exchange Rate

A common problem faced by firms that offshore the manufacture of components/parts/systems relates to dealing with the exchange rate and in particular, when the favorability of offshoring due to significant manpower rate differences $(£1 - £2)$ diminishes. The same problems will also occur when the PD tasks are offshored. Since we are considering that the complete task is offshored, i.e. $A_{nkt} \in \{0, 1\}$, the home location may not be able to react to adverse changes in the manpower rate differences and initiate the offshored tasks back at the home location.

We assume that the home location manpower rate $\ell_1$ remains constant while the offshore manpower rate $\ell_2$ changes with time, i.e. $\ell_{2t}$, and only the exchange rate component of this wage rate changes. We model the exchange rate evolution of manpower rates using the geometric brownian motion which is common in literature (Duffie (2001), Ross (1996), Huchzermeier and Cohen (1996)). Thus, the manpower rate at the GPD location changes as $\ell_{2t} = \ell_{20}.exp\left((\mu_{2t} - \frac{\sigma_{2t}^2}{2})t + \sigma_{2t}.z_t\right)$. Here $\mu_{2t}$ reflects the drift of the manpower rate, $\sigma_{2t}^2$ its volatility, and $z_t \sim N(0, t)$ represents the Brownian motion. Incorporating this for the simultaneous and sequential cases, we get the following proposition:

**Proposition 7: Manpower rate changes at the GPD location:** The optimal effort allocation is independent of the drift of the manpower rate $\mu_2$. However, when both tasks are offshored simultaneously, the optimal effort allocation $B_1^*$ is increasing in the volatility of the manpower rate if $f_1'(B_1)(w_1.g_1 + 2.c.g_2) > f_2'(B - B_1).w_2.g_2$. When the tasks are offshored sequentially, the optimal effort allocation (for both first period and second period offshoring, $B_1^*$ and $B_2^*$) is not increasing in the manpower rate volatility.

The key observation is that the effort prioritization does not depend on the drift but does depend on the volatility of the exchange rate. This shows that the risk-averse firm is apprehensive about the exchange rate volatility. In the simultaneous case, we observe that effort prioritization increases or decreases with the volatility of the exchange rate depending on factors which are independent of the exchange rate (or its movement), and thus observed during the first period. Similarly, in the sequential offshoring case, effort prioritization does not increase (in fact decreases) with exchange rate volatility, thus implying that the firm’s optimal allocation is more driven by factors like $g_n$, modularity, learning rates, etc. Thus the firm attempts to create sufficient competence at the GPD location such that the efficiency differences are minimized to ameliorate the adverse exchange rate volatility.

An interesting observation is that the firm’s optimal allocation does not increase with exchange rate volatility or even when it increases (simultaneous offshoring case), it depends on the first period observations of work time and coordination time. Second period expected time is not considered. This can lead us to deduce that firms, though
risk-averse, tend to be myopic in their decisions when allocating effort, with respect to exchange rate movement.

To summarize, we observe that the firm should prioritize efforts, in the face of uncertainty, to ensure that the efficiency gaps in work time and coordination time are minimized.

4.5 Discussions

Modularity or Learning: We reviewed the prioritization of optimal effort between the two tasks based on the various factors that affect work time and coordination time (within the GPD location and with the home location) in section 4.3. Our findings address the research questions outlined in section 4.1. Now we contrast the effort prioritization based on modularity with that based on other factors that lead to work time and coordination time efficiency differences across locations.

Collating from proposition 1 through proposition 4, we observe:

\[
\begin{align*}
i) & \quad \frac{dB_1}{dL_n} < 0, \quad \frac{dB_1}{dg_1} > 0, \quad \frac{dB_1}{dg_c} > 0 \\
ii) & \quad \frac{dB_1}{dL_n} < 0, \quad \frac{dB_1}{d\mu_1} > 0, \quad \frac{dB_1}{d\mu_2} < 0
\end{align*}
\]

We infer from observation i) above that efforts to support offshoring are prioritized based on the offshoring penalty faced in work time and coordination time, and in particular to those with lower modularity. Low modularity tasks have high coordination requirements, and when faced with significant efficiency differences on the same, efforts need to be prioritized towards managing the extra coordination time required. The key challenge on effort prioritization here comes when the firm needs to decide between a low modularity task with low coordination time efficiency gap and a high modularity task with high efficiency gap. Since effort prioritization is always increasing in offshoring penalty (work time or coordination time), prioritization of offshoring efforts should aim at minimizing the efficiency gap (high modularity will have high work time and low modularity will have high coordination time).

Observation ii) compares the optimal prioritization based on modularity with the ability of the task \((n = 1)\) to provide related benefit to the other task \((\mu_1)\) and/or receive related benefit from the other task \((\mu_2)\), with the corresponding benefits appearing in the learning rate. We observe that effort prioritization for a task should increase as its ability to support the efficiency of other tasks increases, but should decrease if its modularity is high. Similarly if the task is able to improve its efficiency on account of another ‘related’ task being done at the same location, then efforts to support offshoring reduce with increase in benefits from the other task. However effort prioritization is always decreasing with modularity of the task.
4.5. DISCUSSIONS

When a task is offshored, it affects other tasks through two parameters of our model: the index of modularity \((1/\eta_n)\) and the learning effect that is transferred \((\mu_n)\). Observation ii) above compares the respective effects of these factors. We build on this observation hereafter.

Prioritization of tasks for offshoring: \(\mu_1\) is the benefit that the efficiency of the other task gets because task \(n = 1\) is performed at the GPD location (through the learning rate). Thus, performing task \(n = 1\) at the GPD location adds a knowledge/learning element to the location. It creates a knowledge base/competence which other tasks can utilize towards better efficiencies.

Now consider a firm that is involved in the design and development of CES and after decomposition, has been able to identify the various tasks and their respective interdependencies. Then, per existing academic literature (Baldwin and Clark (2000), Anderson et al. (2008), Gomes and Joglekar (2008)), this firm, assuming all other factors are equal, should offshore the task with the highest index of modularity first.

From the above, we observe that there exists a trade-off for a firm when deciding on the task to be offshored. Should they offshore a task based on the index of modularity and minimize coordination challenges? Or should they offshore a task based on its ability to generate knowledge/competence at the offshore location? This trade-off assumes that all other factors are identical between the tasks. Offshoring based on the index of modularity of the task implies immediate efficiency gains through low coordination needs, while offshoring based on ability of the task to generate knowledge/competence implies long term learning rate based efficiency gains. This trade-off is similar to that identified between efficiency (short-term) and learning (long-term) by Sobrero and Roberts (2001). They found that, in supplier-manufacturer relationship, the design scope helps in learning and the interdependencies in both efficiency and learning. We represent our trade-off in Fig. 4-2.

Tasks that are highly modular and can contribute towards knowledge/competence development at the GPD center (Wernerfelt (1984)) should be PRIORITIZED for offshoring. Tasks with low modularity and low knowledge/competence development ability should be avoided for offshoring or SUSTAINED at the home/base location (or offshored after all other tasks have been offshored). The key tradeoff arises when \(\frac{1}{\eta_n} - \mu_1\) are high-low or low-high. As discussed earlier, the impact of modularity is observed from the time period the task is offshored, whereas those of \(\mu_1\) and \(\mu_2\) are observed through the learning rate and hence later (e.g. only from time period \(t = 2\) in the model setup in (4.2.1) or (4.2.3)). Thus, we can say that the impact of effort allocation based on modularity is short-term and thereafter, while that based on related/tacit benefit is long-term.

If effort allocation is based on high modularity, it AUGMENTS the benefit in terms of improved efficiency on the offshored task (high modularity-low knowledge/competence development). On the other hand, in the case of low modularity-high knowledge/competence development, the benefits of the effort expended are more
CHAPTER 4. EFFORT DISTRIBUTION IN GPD

Figure 4-2: Offshoring Prioritization between Modularity and Knowledge Creation

long term (INVESTment) and are visible through better efficiencies in other tasks over time. In this case, efforts need to be exerted to ensure that the coordination challenges on account of low modularity index are handled appropriately. The above trade-off matrix is valid over all time periods as long as all the other factors are constant amongst the tasks under consideration for offshoring. Similar to Sobrero and Roberts (2001), modularity reflects the interdependencies in the structure of the CES and contributes to efficiency (through coordination needs). On the other hand, \( \mu_n \) is like design scope as it involves knowledge creation for other tasks and contributes to learning.

Path dependent offshoring: Our economic modeling (4.2.2) and (4.2.4) and the above discussions on \( \mu_n \) (ability to create knowledge/competence at GPD location for other tasks to benefit from) suggest that the sequence of tasks that are offshored to the GPD location are such that they:

- they gain in efficiency (through learning rate) from other tasks already offshored
- they are able to contribute to the knowledge base/competence at the GPD location to help in the learning rate of the subsequent tasks that are offshored

This implies that the selection of tasks is ‘path dependent’ as defined in dynamic capabilities (DC) literature (Teece et al. (1997), Eisenhardt and Martin (2000)). DC builds on the limitation of the resource based view that it ignores the environment and its dynamics. DC has been defined as the ‘ability to integrate, build, and reconfigure internal and external competencies to address rapidly-changing environments’ (Teece et al. (1997)). GPD is like a DC process with its 3 roles: coordination needs
4.5. DISCUSSIONS

determined by architecture (static content), learning effects in many ways (dynamic content) and work re-assignment (transformational content).

The choice of the offshoring task (as shown above) will depend on previous actions of the firm (tasks that have already been offshored) and future benefits to the firm from offshoring this task, thus displaying path dependent behavior.

Case Example: Consider again the example of Dover (discussed in chapter 2). This example reflects horizontal carryover of learning effects rather than the sequential effects that we have derived in this chapter.

Dover, a unit of Danaher Motion, is engaged in the design, development, and manufacture of air-bearing based precision motion products. Dover’s business involves quick order-to-delivery timeline requiring quick engineering turnaround. Dover initiated its GPD activities by offshoring some PD tasks like drawings, detailing for manufacturing, CAD, etc. Successful completion of these tasks required extensive coordination with other tasks that had not been offshored. Unfortunately Dover experienced significant problems in meeting the turnaround time in the offshored tasks and decided to abort their PD offshoring efforts.

Thereafter, Dover joined the GPD efforts of its parent organization. Danaher Motion established an offshore PD center for all companies in its group. Each company had dedicated project engineers who were trained at the respective companies. Below the project engineers was a pool of flexible engineers who were assigned to various groups based on task/workload requirements. Dover, subsequent to training of its project engineers, offshored the same set of tasks as earlier. They had a better experience as the turnaround time, though not as efficient as at their home location, was more satisfactory. Hence, Dover decided to increase its offshore content, in phases, thereafter.

Why did Dover observe faster turnaround time in their second offshoring effort? There were two reasons: a) they supported their offshoring actions with significant efforts through training and familiarization of the project engineers, and b), the flexible engineers who worked across group companies. Since most of these group companies were engaged in the design and development of mechanical engineering systems, the flexible engineers were required to be trained primarily for the first task that they worked in. As they worked across companies, they could transfer their knowledge and skill gained to the other company’s tasks, and the training effort on part of Danaher Motion reduced. This knowledge and skill portability is similar to $\mu_n$ defined in our model. Dover benefited through the flexible engineers learning by doing something else (related). Thus, Dover’s next offshoring content should be such that those PD tasks benefit from the knowledge and skill set already existing at the offshore PD center, and they also enhance the knowledge and skill set to benefit further tasks that are offshored.
4.6 Conclusion

Our modeling and analysis efforts provide several interesting insights for firms pursuing offshoring of PD tasks for cost saving. We summarize them below:

- Firms should prioritize their offshoring content to develop the knowledge and skill set at the GPD location (long term benefits), rather than prioritizing offshoring content based on index of modularity (short term benefits). The choice of subsequent offshoring content should consider the benefits from the existing knowledge and skill set at the GPD location, and also enhancing the same so that further offshoring efforts gain (path dependence).

- Firms should prioritize efforts to reduce the efficiency gap in the coordination time between tasks that are at different locations before addressing the gap between tasks that are at the GPD location.

- In the face of uncertainty, the risk averse firm exerts higher initial efforts to support the offshoring efforts. This approach helps to minimize the efficiency challenges and develop the knowledge base at the GPD location faster, thus negating any adverse volatility in various exogenous factors.

Though literature has discussed knowledge spillover benefits in significant detail (see Knott (2008)), our recommendation of prioritizing offshoring content so as to create a knowledge base at the GPD location is novel. However, it is accompanied by a key challenge which relates to the ability of the firm to measure or estimate the various variables discussed in our paper. Can firms quantify the benefits to the learning rate from having done other tasks earlier? Are firms measuring and segregating the PD task time between work time and coordination time (we have shown an approach towards the same in chapter 3)? We consider this a challenge of our modeling and analysis approach: it is quite detailed and firms will be challenged in quantifying each variable.

A limitation of our model is that we have not incorporated the impact of the factors on each other, e.g., we have not considered the impact of the effort applied (corresponding to $B_n$ on the learning rates $r_n, r_c, \mu_n$, etc.). However, we do not expect these to impact our results adversely.

While we have developed our results/recommendations based on analytical modeling and have shown a related case example that supports our recommendations, it is desirable to do further empirical studies that confirm our results. It could involve an econometric study (it could be challenging to obtain all the data required and from various firms) involving simultaneous equations, with the work time, the coordination time and the various learning rates (all at the GPD location) as the dependent variables; and with the efforts applied, the GPD location characteristics and several control factors as independent variables.
4.6. CONCLUSION

The base model developed by us (3.2.3) is very general and can also be extended for multiperiod effort allocation (refer Appendix B.10) and for partial offshoring, i.e. $A_{ij} \in [0, 1]$. The partial offshoring case is important when the firm decides to keep some knowledge of the task at the home location. Our overview of these extensions show that they are useful when determining the allocation of efforts between tasks or the relative offshoring content for the tasks, but do not enhance the comparative statics results. We also expect, as a direct consequence of our modeling and analysis efforts, that research towards measuring the various variables of our study will be initiated.

A key extension of our model would be to a buyer-seller scenario when the seller is at the offshore location. In that case the firm designing and developing the CES may face challenges in visibility of actual task completion time by the supplier and that would impact the construction of the contract. There would also be a case of knowledge being lost by offshoring the task (but that would be a make/buy issue rather than a on/off-shore challenge, though the offshore location of the supplier may aggravate the situation). Our results can also lead to studies in understanding the relationship between knowledge/competence development and the index of modularity of the tasks offshored for CES.
CHAPTER 4. EFFORT DISTRIBUTION IN GPD
Chapter 5

Conclusion

The following figure (Fig. 5-1) is a summary of this thesis. The top row has the research questions. The second row outlines the contents of the various chapters. The last row shows the contributions of each chapter.

![Diagram](image)

Figure 5-1: Thesis Summary

We started our research with a system architecture based analysis of the GPD approaches of five firms engaged in the design and development of complex engineered systems. These firms were pursuing GPD seeking cost savings (coupled with engineering capacity hedging) or competence. We observed that process decomposition was the first step towards identification of offshoring content unless the firm was seeking product competence at the offshore location (supplier in this case). However firms continue to be challenged in identifying the offshoring content.

In Chapter 3 we explore the process of identifying, over time, the offshoring content for a firm pursuing GPD for cost savings purposes (setting up an inhouse facility).
We developed a theory based on existing academic literature and modeled a recursive equation to represent our theory. We also identified an index of modularity (ratio of work time to sum of work time and coordination time) for establishing GPD content. We then demonstrated a methodology to apply our theory in an industrial setting. While our optimization efforts highlighted significant cost savings, we found a surprising result: the offshoring content did not follow monotonic behavior. Analysis of the details revealed that this was driven by the work time and coordination time efficiency differences between the locations.

We next developed a stylized model to understand these efficiency differences. We pursued a two-task, two-location, two-time-period model. We found that firms need to prioritize their efforts, while transferring content to the offshore location, so as to establish knowledge/competence at the offshore location, rather than prioritizing the efforts based on modularity of the task. Offshoring based on modularity gives short term payback whilst that based on the ability to create a knowledge/competence has a longer payback duration.

5.1 A Process for Global Product Development

We build on our observations and results of the previous sections to propose a process that firms can follow towards establishing a GPD center (Fig. 5-3). This process is recursive with learnings following through to subsequent periods and the offshore development content changing with time. In Fig. 5-2 we outline the sequence of steps that a firm needs to follow, given its GPD motive. These are part of the system architecture development phase.

![Figure 5-2: Decision Steps for GPD Content](image-url)
5.1. A PROCESS FOR GLOBAL PRODUCT DEVELOPMENT

The first step for a firm is to determine the reason for pursuing GPD. The sequence of steps is determined by this motive and the respective steps have been outlined in Fig. 5-2. For a firm pursuing GPD to meet market needs (we did not have an example in our case studies), the primary GPD content is well established: it is the unique content that needs to be designed and developed for the overseas market. This content development may or may not be accompanied by related manufacturing at the GPD location, e.g. Haier does development for the US market in the USA, though the manufacturing activities continue at its home location in China (Eppinger and Chitkara (2007)). This offshore development may be an inhouse operation or outsourced.

Among firms that pursue GPD for efficiencies, those pursuing competence seeking through complementary knowledge (necessary to complete the system) will have defined content, and design and development will be carried out by a supplier with the associated competence (e.g. Pitney Bowes). The process followed will be similar to that for design and development for specific market needs. However firms that seek competence through incremental knowledge would have the primary offshoring content decided (based on the knowledge that they pursue) but decisions on sourcing strategy and process and product decomposition would be taken in parallel as part of system architecture development. The choice of sourcing strategy will influence the architecture decomposition as planning for coordination is likely to depend on that, and similarly the limitations faced while doing system decomposition would influence the sourcing strategy. Amongst our cases, Intel set up development centers at India and Russia to exploit the engineering talent in these regions, and they were captive development centers. However, they could have also opted for outsourcing such design and development activities: their decision would have been influenced by intellectual property protection, coordination with suppliers, etc.

Firms that pursue efficiencies through cost savings and/or capacity hedging need to first list and then distribute all process-product combinations, i.e. the outcome of hybrid (process followed by product) decomposition exercises, in the 2x2 make/buy in/out (Fig. 1-2) matrix. This will help identify combinations that can be outsourced and those that can be offshored. Through the system architecture development steps, as architecture develops, system decomposition, sourcing decision and offshoring content influence each other towards a final decision on GPD content. We observed that Danaher Motion only offshored ‘general’ or ‘commodity’ engineering tasks to their supplier and tasks involving their core competence were not offshored. Similarly, Cessna offshored both ‘general’ and ‘mission-critical’ tasks but did not outsource the ‘mission-critical’ tasks.

We expand Fig. 1-1 to understand in detail the impact of GPD on the PD process of CES. The key decision on identifying the offshoring content is taken during system architecture development. This phase comprises of concept development, system design, and system architecture approval. Key GPD inputs like GPD motive, details on capabilities of offshore engineering center/location, etc. are required in this phase.
CHAPTER 5. CONCLUSION

Offshore centers (captive and suppliers) may be involved during concept development and system design. We show this as X and Y respectively in Fig. 5-3. When the GPD motive is market needs or competence seeking, the proportionate area of X and Y increases. However, as seen in each case, the system architecture approval is retained at the home location or the competence center. Firms should retain this responsibility inhouse at the home location. This responsibility ensures that the home location/competence center retains control on the design content, interface decisions, onshore/offshore responsibilities, sourcing decisions, etc. Transferring of this decision to an offshore engineering center can lead to serious implications on quality, and in case of CES it is a very long capability transfer process. The ability to approve the final system architecture is a core competence of the firm designing and developing CES. It is built over many years, through a number of product development cycles, and numerous product iterations.

The final offshore content is decided as part of the system architecture decision. Component/task development is now distributed, and this defines the GPD content. The choice of offshore content, besides the cases of market needs and competence seeking, need to ensure that the coordination needs between the various locations
5.2. CONCLUSION

are minimized (Anderson et al. (2008), Eppinger and Chitkara (2007), Gomes and Joglekar (2008)).

Subsequent to component/task development, system integration takes place. Like system development, the offshore engineering center may be involved during system integration proveout (and the area of $Z$ increases with increased offshore content), but the approval of the system integration remains with the home location/competence center. Like approval of system architecture development, the ability to approve system integration is a core competence of the firm. Along with approval of the system architecture development, it is the last responsibility that is likely to be offshored or outsourced.

The work distribution is not static, rather it is dynamic. There needs to exist a regular evaluation process whereby the performance of offshore development work and the coordination efforts are monitored and global work distribution reviewed accordingly. This could include establishment of new GPD centers, allocation of more task content to existing GPD locations, reduction of work allocation to certain GPD locations, etc.

5.2 Conclusion

Global Product Development (GPD) is fast gaining attention as an opportunity that firms can exploit. However, for complex systems, the challenge is immense. While efforts are being made to reduce the difficulties faced in coordination across regions, we have proposed an economic modeling approach to reduce coordination. We have also shown that it may be beneficial for firms to take a long term view and invest in competence and knowledge development through a careful selection of tasks for offshoring. We firmly believe that GPD is an emerging phenomenon. Our findings and proposals reflect the current state of GPD practice and related opportunities therein. We expect that as GPD practice evolves, our findings and proposals will modify accordingly.
Appendix A

Nokia Example: Formulae and Table

A.1 Derivation of Learning Rate Formulae

In section 3.4.3 we had captured the learning rate at the various locations for the work time and coordination time efficiency. We will briefly describe the derivation here. The basic learning curve for time taken to solve a problem (Boone and Ganeshan (2001)) for the $n^{th}$ time is given as $T_n = T_1 \cdot n^{-r}$, where $T_n$ is the time taken for the $n^{th}$ effort, $T_1$ was the time taken the first time and $r$ represents the learning rate. In our case, when we consider the work time efficiency factor for department $j$ at location $k$, i.e. $\phi_{jk}$, the learning (by repeated doing) acts to improve this efficiency factor. Thus, if the task has been performed for $T_k$ periods already, the efficiency factor, with learning rate $r_{jk}$ is given as:

$$\phi_{jk(T_k)} = \phi_{jk1}(T_k)^{(-r_{jk})}$$

Similarly, for time $T_k + t$ it is given as

$$\phi_{jk(T_k+t)} = \phi_{jk1}(T_k + t)^{(-r_{jk})}$$

Combining the above, we get

$$\phi_{jk(T_k+t)} = \frac{\phi_{jk(T_k)}}{(T_k+t)^{-r_{jk}}}$$
The equation is section 3.4.3 assumes that the learning rate is independent of the department $j$ and hence uses $r_k \log r_{jk}$. With Nokia, each program has a total time period of one year and hence we could use the above derived formulae. In case a program is greater than or less than a year, the time factor $T_k$ above will need to be modified accordingly.

The coordination time efficiencies are obtained similar to the work time efficiency derived above.

### A.2 Learning Rate at Nokia

We used the basic learning curve formulae to derive the learning rate at the GPD location. Data available with Nokia had current work time efficiency at 0.6. This was the third year of operation at the GPD location. The earlier efficiencies had been 0.5 and 0.564 in the initial two years. Fitting along a log curve, we approximated a slope of -0.15272 and an intercept of 1.97114 which now represent the learning rate and the first instance time. We used these factors to then derive the work time efficiency at the GPD location for the planning period. We extended the same efficiency for the calculation of the coordination time efficiencies.

### A.3 Coordination Efficiency Table

Based on discussions, we arrived at the following relative coordination efficiency table for coordination between various locations. Thus this represented $\theta_{kk'}$, though ideally we would have liked to have $\theta_{kk'}$.

<table>
<thead>
<tr>
<th>$\theta_{kk'}$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ratio of time taken</th>
<th>1</th>
<th>2</th>
<th>rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>Excellent, no challenges</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Good, little coordination challenges</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Average, some coordination challenges</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Poor, a lot of challenges in coordination</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>No joint activities &amp; coordination</td>
<td></td>
</tr>
</tbody>
</table>

Figure A-1: Relative Coordination Efficiency (between locations)

We also understood that the time difference between ratings 4 and 3 was less than that between 3 and 2, which was less than that between 2 and 1. Thus it was a convex reducing on the time scale. However if we have the rating of 4 to have maximum efficiency of 1, then it is a concave increasing curve starting with efficiency 0.5 corresponding to rating 1 and increasing to efficiency 1 for rating 4. So we started by fitting a convex function with the relative time durations. Thus we used $M x^{-1/4} = 1$ for rating of 4 corresponding to time duration of 2, and $M x^{-1} = 2$ for rating of 1 corresponding to time duration of 1. Solving, we got $x = 0.397$ and $M = 2.52$. 

We used these for ratings of 2 and 3 to get $Mx^{-1/3} = 1.26$ and $Mx^{-1/2} = 1.587$ respectively. Taking the inverse, we get a convex curve of 0.5, 0.63, 0.794, and 1 for ratings of 4,3,2, and 1 respectively. Reversing for coordination efficiency, we get 1, 0.87, 0.706 and 0.503 for ratings of 4,3,2 and 1 respectively and these are transformed to obtain Fig. 3-6. We check for robustness of this transformation in section 3.7.2.
Appendix B

Proofs and Explanation for Stylized Models (Chapter 4)

B.1 Proof of Result 1:

We solve (4.3.2) and (4.3.3) for \( B_1^* \) using the first order condition \( \frac{\partial L}{\partial B_1} = 0 \). We then use the second order differential \( \frac{\partial^2 L}{\partial B_1^2} \) to determine if the first order condition solution meets the minimization criteria. Taking the first order condition \( \frac{\partial L}{\partial B_1} = 0 \), we get:

\[
\frac{\partial L}{\partial B_1} = 0 = e^{-\beta}(l_2.w_1.g_1.f_1'(B_1) - l_2.w_2.g_2.f_2'(B - B_1) + 2.l_2.c.g.c.f_1''(B_1))
+ e^{-2\beta}.(l_2.w_1.g_1.2^{-(r_1+\mu_2)}).f_1'(B_1) - l_2.w_2.g_2.2^{-(r_2+\mu_1)}.f_2'(B - B_1)
+ 2.l_2.c.g.c.2^{-(r_2+\mu_2)}.f_1'(B_1))
\]

\[
\Rightarrow f_1'(B_1).[w_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\mu_2)}) + 2.c.g.c.(1 + e^{-\beta}.2^{-(r_c+\mu_2)})]
= f_2'(B - B_1).[w_2.g_2.(1 + e^{-\beta}.2^{-(r_2+\mu_1)})]
\]

Rearranging gives the result in (4.3.4). Now let us consider the second order differential \( \frac{\partial^2 L}{\partial B_1^2} \).

\[
\frac{\partial^2 L}{\partial B_1^2} = e^{-\beta}(l_2.w_1.g_1.f_1''(B_1) + l_2.w_2.g_2.f_2''(B - B_1) + 2.l_2.c.g.c.f_1''(B_1))
+ e^{-2\beta}.(l_2.w_1.g_1.2^{-(r_1+\mu_2)}.f_1''(B_1) + l_2.w_2.g_2.2^{-(r_2+\mu_1)}.f_2''(B - B_1)
+ 2.l_2.c.g.c.2^{-(r_2+\mu_2)}.f_1''(B_1))
\]
Now let us consider the different cases:

**Case 1:** both \( f_1(B_1) \) and \( f_2(B_2) \) are convex. Then \( f'(B) \geq 0 \) and we get \( \frac{\partial L}{\partial B_1} \geq 0 \). Thus, the first order conditions give us the minimization conditions if a solution exists. If a solution does not exist, then the entire effort is applied to the task that ensures that the total cost is lower, i.e. \((4.2.2)\) is minimized.

**Case 2:** \( f_1(B_1) \) is convex and \( f_2(B_2) \) is concave-convex. Then solve \((4.3.2)\) and find \( B_1^* \) and \( B_2^* \). If a solution exists and \( \frac{\partial L}{\partial B_1} \geq 0 \) then that is the solution. If a solution does not exist or \( \frac{\partial L}{\partial B_1} < 0 \), then the entire effort is applied to the task that ensures that the total cost is lower, i.e. \((4.2.2)\) is minimized.

**Case 3:** both \( f_1(B_1) \) and \( f_2(B_2) \) are concave-convex. Then solve \((4.3.2)\) and find \( B_1^* \) and \( B_2^* \). If a solution exists and \( \frac{\partial L}{\partial B_1} \geq 0 \) then that is the solution. If a solution to \((4.3.2)\) does not exist or \( \frac{\partial L}{\partial B_1} < 0 \), then the entire effort is applied to the task that ensures that the total cost is lower, i.e. \((4.2.2)\) is minimized.

**Note:** Use the other Coordination Term Now let us consider the case where \( \max_n(2^{-(r_c+\mu n)}f_n(B_n)) = 2^{-(r_c+\mu)}f_2(B_2) \) where \( 2^{-(r_c+\mu)} = 2^{-(r_c+\mu)} \)

Substituting in \((4.3.2)\) and \((4.3.3)\) we obtain:

\[
x_{11} = B + e^{-\beta}(l_2(w_2 g_1 f_1(B_1) + w_2 g_2 f_2(B - B_1))) + l_2 c g_c f_1(B_1) + e^{-2\beta}(l_2 w_1 g_1 2^{-(r_1+\mu_2)} f_1(B_1) + l_2 w_2 g_2 2^{-(r_2+\mu_1)} f_2(B - B_1)) + 2 l_2 c g_c 2^{-(r_c+\mu_1)} f_2(B - B_1)
\]

Following similar steps as earlier for the proof, we get:

\[
\frac{\partial L}{\partial B_1} = e^{-\beta}(l_2 w_1 g_1 f_1'(B_1) - l_2 w_2 g_2 f_2'(B - B_1)) + 2 l_2 c g_c f_1'(B_1) + e^{-2\beta}(l_2 w_1 g_1 2^{-(r_1+\mu_2)} f_1'(B_1) - l_2 w_2 g_2 2^{-(r_2+\mu_1)} f_2'(B - B_1)) - 2 l_2 c g_c 2^{-(r_c+\mu_1)} f_2'(B - B_1))
\]

\[
\implies f_1'(B_1)[w_1 g_1(1 + 2^{-(r_1+\mu_2)} + 2 c g_c)] = f_2'(B - B_1)[w_2 g_2(1 + 2^{-(r_2+\mu_1)} + 2 c g_c e^{-\beta} 2^{-(r_c+\mu_1)})]
\]

\[
\implies \frac{f_1'(B_1)}{f_2'(B - B_1)} = \frac{w_2 g_2(1 + 2^{-(r_2+\mu_1)} + 2 c g_c e^{-\beta} 2^{-(r_c+\mu_1)})}{w_1 g_1(1 + 2^{-(r_1+\mu_2)} + 2 c g_c )}
\]

Comparing the above with \((4.3.4)\), we observe that the effort allocation continues to depend on the ratio of the marginal benefits of the effort exerted, with some re-arrangement of the terms. Evaluating for the different cases for \( \frac{\partial L}{\partial B_1} \), we obtain the same results as earlier in the proof. QED.
B.2 Proof of Proposition 1:

We incorporate the definitions of index of modularity in the solution of Result 1 (4.3.4) to get

\[
f'_1(B_1).[w_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\mu_2)}) + 2.\eta_1 - 1).w_1.g_c.(1 + e^{-\beta}.2^{-(r_c+\mu_2)})] \\
= f' (B - B_1).[w_2.g_2.(1 + e^{-\beta}.2^{-(r_2+\mu_1)})] \\
\]

(B.2.1)

Now for each of the comparative statics terms we need to use the envelope theorem.

B.2.1 Modularity

For the index of modularity \( \frac{1}{\eta} = \frac{w_n}{w_n + c} \), we have

\[
\frac{dB_1}{d\eta_1} = \frac{dB_1}{d\eta_1} \cdot \frac{d\eta_1}{d\eta} = -\eta_1^2 \cdot \frac{d\eta_1}{d\eta} \quad \left( \frac{d\eta}{d\eta_1} = -\frac{1}{\eta_1} \right)
\]

Now applying \( \frac{dB_1}{d\eta_1} \) on (B.2.1) we get

\[
\frac{dB_1}{d\eta_1} (f''(B_1).[w_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\mu_2)}) + 2.\eta_1 - 1).w_1.g_c.(1 + e^{-\beta}.2^{-(r_c+\mu_2)}) \\
+ f''(B - B_1).[w_2.g_2.(1 + e^{-\beta}.2^{-(r_2+\mu_1)})]) \\
= -2.f'_1(B_1).w_1.g_c.(1 + e^{-\beta}.2^{-(r_c+\mu_2)}) \\
\Rightarrow dB_1 = \frac{-2.f'_1(B_1).w_1.g_c.(1 + e^{-\beta}.2^{-(r_c+\mu_2)})}{M} \\
\]

where \( M = f''_1(B_1).[w_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\mu_2)}) + 2.\eta_1 - 1).w_1.g_c.(1 + e^{-\beta}.2^{-(r_c+\mu_2)}) + f''(B - B_1).[w_2.g_2.(1 + e^{-\beta}.2^{-(r_2+\mu_1)})]) \)

Now \( M \geq 0 \) (by proof of Result 1 this condition is required for (4.3.4) to be the solution). Thus, \( \frac{dB_1}{d\eta_1} > 0 \) and \( \frac{dB_1}{d\eta} < 0 \) as \( f'_1(B_1) < 0 \).

B.2.2 Learning by Doing Something Else

We follow the same steps as in the previous proof applying \( \frac{dB_1}{d\mu_1} \) and \( \frac{dB_1}{d\mu_2} \) to (B.2.1). We get:

\[
\frac{dB_1}{d\mu_1} = A_1 \quad \frac{dB_1}{d\mu_2} = A_2 \quad \text{where } M \text{ is as defined in (B.2.2)} \\
A_1 = -(-1).w_2.g_2.e^{-\beta}.f''(B - B_1).2^{-(r_2+\mu_2)}.ln(2) \\
A_2 = -(-1).w_1.g_1.e^{-\beta}.f'_1(B_1).2^{-(r_1+\mu_2)}.ln(2) \\
\quad -(-1).2.\eta_1 - 1).w_1.g_c.f'_1(B_1).2^{-(r_c+\mu_2)}.ln(2)
\]
Since $f_n(B_n)$ is convex reducing, $f'_n(B_n) < 0$. Hence $A1 > 0$ and $A2 < 0$ and we already have $M > 0$. So we get $\frac{dB_1}{d\mu_1} > 0$ and $\frac{dB_1}{d\mu_2} < 0$.

### B.2.3 Learning by Repeated Doing

We follow the same steps as in the previous proofs applying $\frac{dB_1}{d\mu_1}$, $\frac{dB_2}{d\mu_2}$ and $\frac{dB_1}{d\mu_2}$ to (B.2.1). We get:

\[
\begin{align*}
\frac{dB_1}{d\mu_1} &= B_1 \frac{dB_1}{d\mu_2} = B_2 \frac{dB_1}{d\mu_3} = B_3, \quad \text{where } M \text{ is as defined in (B.2.2)}
\end{align*}
\]

\[
\begin{align*}
B_1 &= -(1).w_1.g_1.e^{-\beta}.f'_1(B_1).2^{-(r_1+\mu_2)} \ln(2)
B_2 &= -(1).w_2.g_2.e^{-\beta}.f'_2(B - B_1).2^{-(r_2+\mu_1)} \ln(2)
B_3 &= -(1).2.(\eta_1 - 1).w_1.g_c.f'_1(B_1).2^{-(r_c+\mu_2)} \ln(2)
\end{align*}
\]

Since $f_n(B_n)$ is convex reducing, $f'_n(B_n) < 0$. Hence $B1 < 0$, $B2 > 0$ and $B3 < 0$ and we already have $M > 0$. So we get $\frac{dB_1}{d\mu_1} < 0$, $\frac{dB_2}{d\mu_2} > 0$ and $\frac{dB_1}{d\mu_2} < 0$.

### B.2.4 Offshoring Penalty

We follow the same steps as in the previous proofs applying $\frac{dB_1}{d\eta_1}$, $\frac{dB_2}{d\eta_2}$ and $\frac{dB_1}{d\nu}$ to (B.2.1). We get:

\[
\begin{align*}
\frac{dB_1}{d\eta_1} &= C_1 \frac{dB_1}{d\eta_2} = C_2 \frac{dB_1}{d\eta_3} = C_3, \quad \text{where } M \text{ is as defined in (B.2.2)}
\end{align*}
\]

\[
\begin{align*}
C_1 &= -f'_1(B_1).w_1.(1 + e^{-\beta}.2^{-(r_1+\mu_2)})
C_2 &= f'_2(B - B_1).w_2.g_2.(1 + e^{-\beta}.2^{-(r_2+\mu_1)})
C_3 &= -f'_1(B_1).2.(\eta_1 - 1).w_1.(1 + e^{-\beta}.2^{-(r_c+\mu_2)})
\end{align*}
\]

Since $f_n(B_n)$ is convex reducing, $f'_n(B_n) < 0$. Hence $C1 > 0$, $C2 < 0$ and $C3 > 0$ and we already have $M > 0$. So we get $\frac{dB_1}{d\eta_1} > 0$, $\frac{dB_2}{d\eta_2} < 0$ and $\frac{dB_2}{d\eta_3} > 0$. QED.

We will outline all the remaining proofs briefly as they follow the same line of reasoning as the proofs of Result 1 and Proposition 1. We will outline them as for Case 1 of Result 1’s proof.

### B.3 Proof of Result 2:

We use the formulations for the sequential offshoring case ((4.2.3) and (4.2.4)) and the assumption of $\max(2^{-(r_1+\delta_1+\nu_2)}.f_1(B_1),(1 + e)^{-\delta_2\mu_1}.f_2(\nu B_2)) = 2^{-(r_1+\delta_1+\nu_2)}.f_1(B_1)$. Taking the other term changes the form of the solution slightly but does not change the comparative statics results. We form the Lagrangean (similar to (4.3.1) and using
B.3. PROOF OF RESULT 2:

\[ B = \sum_n B_n \] or \[ B_2 = e^{\beta}(B - B_1) \] as follows:

\begin{align*}
L(B_1) &= B_1 + e^{-\beta}.(e^{\beta}(B - B_1) + \ell_2.w_1.g_1.f_1(B_1) + \ell_1.w_2 \\
&\quad + (\ell_1 + \ell_2).c.g_1.f_1(B_1)) + e^{-2\beta}.(\ell_2.w_1.g_1.f_1(B_1).2^{-(r_1+\delta_1\mu_2)} \\
&\quad + \ell_2.w_2.g_2.f_2(\nu.e^{\beta}(B - B_1)).(1 + e)^{-\delta_2\mu_1} + 2.\ell_2.c.g_1.f_1(B_1)))
\end{align*}

(B.3.1)

Taking the first derivative as in Result 1, we get:

\[
\frac{\partial L}{\partial B_1} = 0 = 1 + e^{-\beta}(-e^\beta + \ell_2.w_1.g_1.f_1'(B_1) + (\ell_1 + \ell_2).c.g_1.f_1'(B_1)) \\
&\quad + e^{-2\beta}.(\ell_2.w_1.g_1.f_1'(B_1).2^{-(r_1+\delta_1\mu_2)} + 2.\ell_2.c.g_1.f_1'(B_1)) \\
&\quad - \ell_2.w_2.g_2.\nu.e^{\beta}.f_2'(\nu.e^{\beta}(B - B_1)).(1 + e)^{-\delta_2\mu_1}
\]

Solving the above we get the solution outlined in Result 2 (4.3.5). It can be shown that the second derivative \(\frac{\partial^2 L}{\partial B_1^2} \geq 0\) as we are considering the convex case. In a similar way, the solution can be obtained for the other term in

\[ \max(2^{-(r_1+\delta_1\mu_2)}f_1(B_1),(1 + e)^{-\delta_2\mu_1}.f_2(\nu B_2)) \]

Now, taking \(B_1 = B - e^{-\beta} B_2\), we get

\begin{align*}
L(B_2) &= B - e^{-\beta}B_2 + e^{-\beta}.(B_2 + \ell_2.w_1.g_1.f_1(B - e^{-\beta}B_2) + \ell_1.w_2 + (\ell_1 + \ell_2).c.g_1.f_1(B - e^{-\beta}B_2)) \\
&\quad + e^{-2\beta}.(\ell_2.w_1.g_1.f_1(B - e^{-\beta}B_2).2^{-(r_1+\delta_1\mu_2)} \\
&\quad - \ell_2.w_2.g_2.\nu.f_2(\nu B_2).(1 + e)^{-\delta_2\mu_1} + 2.\ell_2.c.g_1.f_1(B - e^{-\beta}B_2)))
\end{align*}

Solving the above for \(\frac{\partial L}{\partial B_2} = 0\), we get the solution

\begin{align*}
\frac{f_2'(\nu B_2^*)}{f_1'(B - e^{-\beta}B_2^*)} &= \frac{\ell_2.w_1.g_1 + (\ell_1 + \ell_2).c.g_1 + e^{-\beta}.(\ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)} + 2.\ell_2.c.g_1.2^{-(r_1+\delta_1\mu_2)})}{e^{-\beta}\ell_2.w_2.g_2.\nu.(1 + e)^{-\delta_2\mu_1}}
\end{align*}

(B.3.2)

This will be the solution if the second order conditions are satisfied.

If the above solution (ratio of marginal benefits) does not exist, then all the efforts are to be prioritized for the task that ensures that total cost (4.2.4) is minimized. In such a case, there may exist a condition wherein no effort is applied to support the first task that is offshored and all the effort supports the task that is offshored at \( t = 2 \). QED.
B.4 Proof of Proposition 2:

We first apply the definitions of index of modularity (3.2.2) to (4.3.5) and (B.3.2) to obtain:

\[
\begin{align*}
    f'_1(B_1^*).(\ell_2.w_1.g_1 + (\ell_1 + \ell_2).(\eta_1 - 1)w_1.g_c \\
    + e^{-\beta}(2.\ell_2.(\eta_1 - 1)w_1.g_c.2^{-(r_1+\delta_1\mu_2)} + \ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)}) \\
    - f'_2(\nu.e^\beta.(B - B_1^*)).(\ell_2.w_2.g_2.\nu.(1 + \epsilon)^{-\delta_2\mu_1}) = 0 \\
    f'_2(\nu B_2^*).(e^{-\beta}\ell_2.w_2.g_2.\nu.(1 + \epsilon)^{-\delta_2\mu_1}) \\
    - f'_1(B - e^{-\beta}B_2^*).(\ell_2.w_1.g_1 + (\ell_1 + \ell_2).(\eta_2 - 1)w_2.g_c \\
    + e^{-\beta}(\ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)} + 2.\ell_2.(\eta_2 - 1)w_2.g_c.2^{-(r_1+\delta_1\mu_2)}) = 0
\end{align*}
\]

We apply the envelope theorem (as in the proof of Proposition 1) to (B.4.1) and (B.4.2) above.

B.4.1 Modularity

We had identified modularity as \( \frac{1}{\eta_n} = \frac{w_n}{w_n+c} \). Thus we get

\[
\frac{dB_1}{d\eta_1} = \frac{dB_1}{d\eta_1} = -\eta_1^2 \cdot \frac{dB_1}{d\eta_1} \quad \left( \frac{d\frac{1}{\eta_1}}{d\eta_1} = -\frac{1}{\eta_1^2} \right)
\]

So differentiating the optimality equation (B.4.1), we get for \( \frac{dB_1}{d\eta_1} \),

\[
\begin{align*}
    &\frac{dB_1}{d\eta_1} (f''(B_1),[\ell_2.w_1.g_1 + (\ell_1 + \ell_2).(\eta_1 - 1)w_1.g_c + e^{-\beta}(\ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)} \\
    + 2.\ell_2.(\eta_1 - 1)w_1.g_c.2^{-(r_1+\delta_1\mu_2)}) \\
    + f'_2(\nu.e^\beta.(B - B_1^*)),[\ell_2.w_2.g_2.\nu.2^{\epsilon}(1 + \epsilon)^{-\delta_2\mu_1}) \\
    = &- f'_1(B_1).2.\ell_2.w_1.g_c.2^{-(r_1+\delta_1\mu_2)} \\
    \Rightarrow \frac{dB_1}{d\eta_1} = &- f'_1(B_1).2.\ell_2.w_1.g_c.2^{-(r_1+\delta_1\mu_2)} \\
    &= \frac{M1}{M1}, \quad \text{where}
\end{align*}
\]

\[
M1 = f''(B_1),[\ell_2.w_1.g_1 + (\ell_1 + \ell_2).(\eta_1 - 1)w_1.g_c \\
+ e^{-\beta}(\ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)} + 2.\ell_2.(\eta_1 - 1)w_1.g_c.2^{-(r_1+\delta_1\mu_2)}) \\
+ f'_2(\nu.e^\beta.(B - B_1^*)),[\ell_2.w_2.g_2.\nu.2^{\epsilon}(1 + \epsilon)^{-\delta_2\mu_1}]
\]

Now \( M1 \geq 0 \) (by proof of Result 2 and for solution (4.2.4) to exist). Thus, as in Proposition 1, \( \frac{dB_1}{d\eta_1} < 0 \).

Repeating the same steps for \( B_2 \) and index of modularity, \( \frac{1}{\eta_2} \), we obtain (from
B.4. PROOF OF PROPOSITION 2:

(B.4.2),

\[ \frac{dB_2}{dn_2} \left( f_2''(\nu_1B_2,\nu_1,\nu_2) \right) \left( e^{-\beta}(l_2.w_2.g_2.\nu_1)(1 + \epsilon)^{-\delta_1\mu_1} \right) \]

\[ + f_1''(\nu_2\epsilon_2 B_2,\nu_2,\epsilon_2) \left( \epsilon_2w_2.g_2.\nu_2 \right) \left( (\ell_2 \cdot \ell_2).w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \right) \]

\[ + e^{-\beta}(\ell_2.w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \cdot (\ell_2 \cdot \ell_2).w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \cdot (\ell_2 \cdot \ell_2).w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \) \]

\[ = f_1'(B - e^{-\beta}B_2) \left( (\ell_1 + \ell_2).w_2.g_2 + e^{-\beta}(\ell_2 \cdot \ell_2).w_2.g_2.2^{-r_1 + (\delta_1 \cdot \mu_2)} \right) \]

\[ \Rightarrow \frac{dB_2}{dn_2} = \frac{f_1'(B - e^{-\beta}B_2) \left( (\ell_1 + \ell_2).w_2.g_2 + e^{-\beta}(\ell_2 \cdot \ell_2).w_2.g_2.2^{-r_1 + (\delta_1 \cdot \mu_2)} \right)}{M_2} \]

\[ M_2 = f_2''(\nu_1B_2,\nu_1,\epsilon_2) \left( e^{-\beta}(l_2.w_2.g_2.\nu_1)(1 + \epsilon)^{-\delta_2\mu_1} \right) \]

\[ + f_1''(B - e^{-\beta}B_2,\epsilon_2) \left( \epsilon_2w_2.g_2.\nu_2 \right) \left( (\ell_2 \cdot \ell_2).w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \right) \]

\[ + e^{-\beta}(\ell_2.w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \cdot (\ell_2 \cdot \ell_2).w_2.g_2.\eta_2 \cdot \eta_2 \cdot r_1 + (\delta_1 \cdot \mu_2) \) \]

Now, \( M_2 \geq 0 \) (by proof of Result 2 and for solution to (4.2.4) to exist). So we now get \( \frac{dB_2}{dn_2} < 0 \) or \( \frac{dB_2}{dn_2} > 0 \).

B.4.2 Other Parameters

We follow the same steps as in the proof of Proposition 2. However, unlike Proposition 2, the effect on \( B_1^* \) and \( B_2^* \) have to be considered separately. We use the envelope theorem on (B.4.1) for the effect on \( B_1^* \) to observe the following:

\[ \frac{dB_1}{d\mu_1} = \frac{f_2''(\nu_1B_1,\nu_1,\mu_1.\ln(1 + \epsilon))(1 + \epsilon)^{-\delta_1\mu_1}.(\delta_2)}{M_1} > 0 \]

\[ \frac{dB_1}{d\mu_2} = \frac{X}{M_1} < 0 \]

where \( X = -f_1'(B_1) \left( e^{-\beta}(l_2.w_2.g_1.\ln 2.2^{-r_1 + (\delta_1 \cdot \mu_2)} \cdot (\delta_1) \right) \]

\[ + 2.l_2.(\eta_1 - 1).w_1.g_2.\ln 2.2^{-r_1 + (\delta_1 \cdot \mu_2)} \cdot (\delta_1) \]

\[ \frac{dB_1}{d\eta_1} = \frac{f_1'(B_1) \left( e^{-\beta}(l_2.w_2.g_1.\ln 2.2^{-r_1 + (\delta_1 \cdot \mu_2)} \cdot (\delta_1) \right)}{M_1} < 0 \]

\[ \frac{dB_1}{d\eta_2} = \frac{f_1'(B_1) \left( e^{-\beta}(l_2.w_2.g_1.\ln 2.2^{-r_1 + (\delta_1 \cdot \mu_2)} \cdot (\delta_1) \right)}{M_1} < 0 \]

\[ \frac{dB_1}{d\delta_1} = \frac{f_1'(B_1) \left( l_1 + \ell_2 \right) \cdot (\eta_1 - 1).w_1}{M_1} > 0 \]

\[ \frac{dB_1}{d\delta_2} = \frac{f_1'(B_1) \left( l_2.w_1 + e^{-\beta}(l_2.w_1.2^{-r_1 + (\delta_1 \cdot \mu_2)} \right)}{M_1} > 0 \]

\[ \frac{dB_1}{d\mu_2} = \frac{f_1'(B_1) \left( l_2.w_1 + e^{-\beta}(l_2.w_1.2^{-r_1 + (\delta_1 \cdot \mu_2)} \right)}{M_1} > 0 \]
Similarly, we use the envelope theorem on (B.4.2) for the effect on $B_2^*$:

\[
d_B^2 = -f_2'(vB_2).e^{-\beta \ell_2.w_2.g_2.\nu}.(1 + \epsilon) - \delta u_1 ln(1 + \epsilon).(-\delta_2) < 0
\]

\[
d_{u_1} = X_B^2 > 0
\]

\[
d_B^2 = \frac{X_2}{M_2} > 0
\]

where $X_1 = f_1'(B - e^{-\beta}B_2).e^{-\beta} \ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)}ln2.(-\delta_1)$

\[
d_B^2 = \frac{f_1'(B - e^{-\beta}B_2).e^{-\beta} \ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)}ln2.(-1)}{M_2} > 0
\]

\[
d_{r_1c} = \frac{f_1'(B - e^{-\beta}B_2).e^{-\beta} \ell_2.w_1.(\eta_2 - 1).w_2.g_2.2^{-(r_1+\delta_1\mu_2)}ln2.(-1)}{M_2} > 0
\]

\[
d_B^2 = \frac{f_1'(B - e^{-\beta}B_2).e^{-\beta} \ell_2.w_1.g_1.2^{-(r_1+\delta_1\mu_2)}ln2.(-1)}{M_2} < 0
\]

B.5 Proof of Proposition 3:

We use the work time and coordination time outlined in Table 4.1 and the prior argument of $B = \sigma_n B_n$ to develop the associated Lagrangean. Solving the Lagrangean (similar to proof of Result 1), we obtain the solution for $B_1^*$ as:

\[
f_1'(B_1^*)(\ell_2.w_1.g_1 + \ell_2.2.c.g_c + (\ell_1 + \ell_2).c_1.g_c) + e^{-\beta}(\ell_2.w_1.g_1.2^{-(r_1+\mu_2)} + \ell_2.2.c.g_c.2^{-(r_c+\mu_2)} + (\ell_1 + \ell_2).c_1.g_c.2^{-(r_c+\mu_2)})
\]

\[
-f_2'(B - B_1^*)(\ell_2.w_2.g_2 + (\ell_1 + \ell_2).c_2.g_c + e^{-\beta}(\ell_2.w_2.g_2.2^{-(r_2+\mu_1)} + (\ell_1 + \ell_2).c_2.g_c.2^{-(r_c+\mu_1)}) = 0
\]

Now substituting the definitions of index of modularity and index of within modularity (for $c = (\eta_{10} - 1)w_1$ and $c_1 = (\eta_1 - \eta_{10})w_1$ in (B.5.1)) and applying the envelope theorem, we observe that

\[
\frac{dB_1}{d\eta_{10}} = \frac{A_1}{M_3}, \text{ where}
\]

\[
A_1 = -f_1'(B_1)(\ell_2.2.g_c.w_1 - (\ell_1 + \ell_2).g_c.w_1 + e^{-\beta}(\ell_2.2.g_c.w_1.2^{-(r_2+\mu_2)} - (\ell_1 + \ell_2).w_1.g_c.2^{-(r_c+\mu_2)})
\]
B.6. PROOF OF PROPOSITION 4:

We use the work time and coordination time outlined in Table 4.2 and the prior argument of $B = \sigma_nB_n$ to develop the associated Lagrangean. Solving the Lagrangean (similar to proof of result 1), we obtain the solution for $B_1^*$ as:

\[
(1 - e^{-\beta}) + f_1'(B_1^*).e^{-\beta}.(\ell_2.w_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\delta)}))
\]
\[
+ (\ell_1 + \ell_2).c_1.g_1.(1 + e^{-\beta}.2^{-(r_1+\delta=\mu2)}) + (\ell_1 + \ell_2).c.g_2 + e^{-\beta}.2.\ell_2.c.g.2^{-(r_1+\delta)}
\]
\[
-k.f_2'(k(B - B_1^*)).e^{-\beta}.(\ell_2.w_2.g_2.(1 + \epsilon)^{-(r_2+\mu_1)})
\]
\[
+(\ell_1 + \ell_2).c_2.g.(1 + \epsilon)^{-(r_2+\mu_1)} = 0
\]

Similarly for index of modularity and the learning rate (by doing something else),

\[
\frac{dB_1}{d\eta_1} = \frac{A_2}{M_3}, \text{ where } A_2 = -f_1'(B_1).e^{-\beta}.(\ell_1 + \ell_2).g_1.(1 + e^{-\beta}.2^{-(r_1+\delta)}) > 0
\]
\[
\Rightarrow \frac{dB_1}{d\eta_1} > 0, \Rightarrow \frac{dB_1}{d\eta_1} < 0
\]

\[
\frac{dB_1}{d\mu_1} = \frac{A_3}{M_3}, \text{ where } A_3 = f_2'(B - B_1).e^{-\beta}.(\ell_2.w_2.g_2.2^{-(r_2+\mu_1)}.ln2.(-1)
\]
\[
+(\ell_1 + \ell_2).c_2.g_2.2^{-(r_2+\delta)}.ln2.(-1))
\]
\[
\Rightarrow A_3 > 0 \Rightarrow \frac{dB_1}{d\mu_1} > 0
\]

\[
\frac{dB_1}{d\mu_2} = \frac{A_4}{M_3}, \text{ where } A_4 = -f_1'(B_1).e^{-\beta}.(\ell_2.w_1.g_1.2^{-(r_1+\mu_2)}.ln2.(-1)
\]
\[
+(\ell_1 + \ell_2).c.g_2.2^{-(r_1+\delta)}.ln2.(-1) + (\ell_1 + \ell_2).c_1.g_1.2^{-(r_1+\delta)}.ln2.(-1))
\]
\[
\Rightarrow A_4 > 0 \Rightarrow \frac{dB_1}{d\mu_2} < 0 \quad \text{QED}
\]
Now substituting the definitions of index of modularity and index of within modularity (for \(c = (\eta_{10} - 1)w_1\) and \(c_1 = (\eta_1 - \eta_{10})w_1\) in (B.6.1)) and applying the envelope theorem, we observe that,

\[
\frac{dB_1}{d\eta_{10}} = \frac{A5}{M4}, \quad \text{where} \quad A5 = -f'_1(B_1).(-(\ell_1 + \ell_2).w_1.g_{c_1}.(1 + e^{-\beta}.2^{-(r_{c_1}+\delta_1.\mu_2)})
+ (\ell_1 + \ell_2).w_1.g_{c_1} + e^{-\beta}.2.\ell_2.w_1.g_{c_1}.2^{-(r_{c}+\delta_2)})
\]

Now we can assume that \(g_{c_1} \approx g_{c_2}\) since both involve coordination (for the first time) between task \(n = 1\) at the GPD location and \(n = 2\) and other tasks at the home location. Also we have \(h < 1\) and since the coordination of \(n = 1\) and \(n = 2\) has the advantage of efforts being applied to support the offshoring of both tasks while the coordination of \(n = 1\) and the other tasks has efforts being applied to support \(n = 1\) only, and coordination between \(n = 1\) and \(n = 2\) is at the same location while that between \(n = 1\) and the other tasks is across locations; we can assume that \(2^{-(r_{c_1}+\delta_1.\mu_2)} > 2^{-(r_{c}+\delta_2)}\). Thus,

\[
\Rightarrow A5 < 0
M4 = f''_1(B_1).e^{-\beta}.(\ell_2.w_1.g_{c_1}.(1 + e^{-\beta}.2^{-(r_{c_1}+\delta_1.\mu_2)}) + (\ell_1 + \ell_2).c.g_{c_2}
+ (\ell_1 + \ell_2).c_1.g_{c_1}.(1 + e^{-\beta}.2^{-(r_{c_1}+\delta_1.\mu_2)}) + e^{-\beta}.2.\ell_2.c.g_{c_1}.2^{-(r_{c}+\delta_2)})
- k^2.f''_2(k(B - B_1)).e^{-2\beta}.(\ell_2.w_2.g_2.(1 + \epsilon)^{-(r_2+\mu_2)})
+ (\ell_1 + \ell_2).c_2.g_{c_2}.(1 + \epsilon)^{-(r_{c_2}+\delta_2.\mu_1)})
\Rightarrow M4 > 0
\Rightarrow \frac{dB_1}{d\eta_{10}} < 0, \quad \Rightarrow \frac{dB_1}{d\eta_{10}} > 0
\]

Similarly for index of modularity and the learning rate (by doing something else),

\[
\frac{dB_1}{d\eta_1} = \frac{A6}{M4}, \quad \text{where} \quad A6 = -f'_1(B_1).e^{-\beta}.(\ell_1 + \ell_2).g_{c_1}.w_1.((1 + e^{-\beta}.2^{-(r_{c_1}+\delta_1.\mu_2)}) > 0
\Rightarrow \frac{dB_1}{d\eta_1} > 0, \quad \Rightarrow \frac{dB_1}{d\eta_1} < 0
\]

\[
\frac{dB_1}{d\mu_1} = \frac{A7}{M4}, \quad \text{where} \quad A7 = -k.f'_2(k(B - B_1)).e^{-2\beta}.(\ell_2.c.g_2.((1 + \epsilon)^{-(r_2+\mu_2)}.ln(1 + \epsilon).(-1))
+ (\ell_1 + \ell_2).c_2.g_{c_2}.((1 + \epsilon)^{-(r_{c_2}+\delta_2.\mu_1)}.ln(1 + \epsilon).(-h_2))
\Rightarrow A7 > 0 \quad \Rightarrow \frac{dB_1}{d\mu_1} > 0
\]
B.7 PROOF OF PROPOSITION 5:

$$\frac{dB_1}{d\mu_2} = \frac{A8}{M4} \text{ where }$$

$$A8 = -f_1'(B_1). (\ell_2.w_1.g_1.e^{-\beta}.2^{-(r_1+\delta\mu_2)}.ln2.(-\delta)$$
$$+2.e^{-\beta}.\ell_2.c.g_c.2^{-(r_c+\delta\mu_2)}.ln2.(-\delta))$$
$$+(\ell_1 + \ell_2).c_1.g_{c1}.e^{-\beta}.2^{-(r_{c1}+h_1\delta\mu_2)}.ln2.(-h\delta)$$

$$\Rightarrow A8 < 0 \Rightarrow \frac{dB_1}{d\mu_2} < 0$$

In the sequential offshoring case, we also need to review the sensitivity of the effort allocation for the second task to be offshored. We repeat the above steps for $B_2$ and observe that:

$$\frac{dB_2}{d\mu_2} > 0, \quad \frac{dB_2}{d\mu_1} < 0, \quad \frac{dB_2}{d\mu_1} > 0, \quad \frac{dB_2}{d\mu_1} < 0 \quad \text{QED.}$$

B.7 Proof of Proposition 5:

Now $E[x^2] = E[e^{x^2}] = E[e^{x^2}]$ and if $x \sim N(\mu, \sigma^2)$, then $E[x] = e^{\mu + \frac{\sigma^2}{2}}$. We can apply this transformation to (4.2.1) and (4.2.3), e.g. $E[2^{-x}] = E[e^{-(r_1+\mu_2).ln2}] = e^{-\ln2.(r_1+\mu_2)+ln2^2.\frac{\sigma^2}{2}}$. We take the utility function of the total cost and form the Lagrangian. We then take the first order conditions to identify the optimal effort distribution (using $U'(x) < 0$) and then apply the envelop theorem for the comparative statics (using $U'(x) < 0$ and $U''(x) < 0$).

Thus, for the simultaneous offshoring case (from (4.2.2)), we obtain,

$$x = B + e^{-\beta}.(\ell_2.\sum w_n.g_n.f_n(B_n) + 2.\ell_2.c.g_c.f_c(B_1))$$
$$+e^{-2\beta}.(\ell_2.\sum w_n.g_n.f_n(B_n) .e^{-\ln2.(r_\text{c1}+\mu_2)+ln2^2.\frac{\sigma^2}{2}}$$
$$+2.\ell_2.c.g_c.f_c(B_1).e^{-\ln2.(r_\text{c1}+\mu_2)+ln2^2.\frac{\sigma^2}{2}})$$

Taking the FOC with respect to $B_1$ and with $B = B_1 + B_2$, we get:

$$U'(x). \left[ g_1.f_1'(B_1).w_1.(1 + e^{-\beta}.e^{-\ln2.(r_\text{c1}+\mu_2)+ln2^2.\frac{\sigma^2}{2}}) \right.$$
$$+2.g_c.f_c'(B_1).(\eta_1 - 1).w_1.(1 + e^{-\beta}.e^{-\ln2.(r_\text{c1}+\mu_2)+ln2^2.\frac{\sigma^2}{2}})$$
$$-g_2.f_2'(B - B_1).w_2.(1 + e^{-\beta}.e^{-\ln2.(r_\text{c1}+\mu_2)+ln2^2.\frac{\sigma^2}{2}}) \right] = 0$$
This gives the $B_1^*$ and hence $B_2^*$ provided the SOC are satisfied. The SOC is given by

$$\frac{\partial^2 L}{\partial B_1^2} = U''(x).|Z|^2 + U'(x).\frac{\partial Z}{\partial B_1},$$

where $U'(x).Z = 0$ (by FOC conditions $Z = 0$)

Inspection shows that this is always $\leq 0$ and hence the FOC give utility maximizing conditions. Now applying the envelope theorem on the FOC conditions, we get

$$\left[U''(x).|Z|^2 + U'(x).\frac{\partial Z}{\partial B_1}\right] \frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} = -U''(x).Z.e^{-2\beta}\kappa_2.w_1.g_1.\frac{(ln2)^2}{2}.e^{-ln2.(\tau_1+\mu_2)+(ln2)^2\cdot\frac{\sigma_{\tau_1,\mu_2}^2}{2}}$$

$$-U'(x).g_1.\frac{(ln2)^2}{2}.e^{-\beta}\cdot e^{-ln2.(\tau_1+\mu_2)+(ln2)^2\cdot\frac{\sigma_{\tau_1,\mu_2}^2}{2}}$$

$$\Rightarrow \frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0.$$ Similarly, $\frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0$, and $\frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} < 0$

Performing similar transformations on (B.5.1) and applying the envelope theorem, we obtain

$$\frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} < 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} < 0$$

We repeat the same steps for the sequential offshoring case, and we obtain

$$\frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} < 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} < 0$$

Performing similar transformations on (B.6.1) and applying the envelope theorem, we obtain

$$\frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_1,\mu_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} < 0, \quad \frac{dB_1}{d\sigma_{\tau_2,\mu_2}^2} < 0$$

QED.
B.8 Proof of Proposition 6:

For the simultaneous offshoring case (from (4.2.2)), we obtain,

\[ E[x] = B + e^{-\beta}(\ell_2 \sum_n w_n \cdot g_n \cdot f_n(B_n) + 2 \ell_2 \cdot E[\eta_1 - 1] \cdot w_1 \cdot g_c \cdot f_c(B_1)) \]

\[ + e^{-2\beta}(\ell_2 \sum_n w_n \cdot g_n \cdot f_n(B_n) \cdot 2^{-(\mu_1 + \gamma_1)} + 2 \ell_2 \cdot E[\eta_1 - 1] \cdot w_1 \cdot f_c(B_1) \cdot 2^{-(\gamma_1 + \mu_1)}) \]

\[ \text{Var}[x] \equiv \sigma_x^2 = e^{-2\beta} 4 \ell_2^2 \cdot \sigma_{\eta_1}^2 \cdot w_1^2 \cdot g_c^2 \cdot (f_c(B_1))^2 \]

\[ + e^{-4\beta} 4 \ell_2^2 \cdot w_1^2 \cdot g_c^2 \cdot \sigma_{\eta_1}^2 \cdot (f_c(B_1))^2 \cdot (2^{-(\gamma_1 + \mu_1)})^2 \]

From \( E[U(x)] = \frac{1}{a} - \frac{1}{a} e^{-aE[x]} + \frac{1}{2} a^2 \cdot \sigma_x^2 \), taking FOC, we get \( \frac{d}{dB_1} E[U(x)] = 0 \)

\[ \Rightarrow \frac{1}{a} \cdot e^{-aE[x]} + \frac{1}{a} a^2 \cdot \sigma_x^2 \cdot \frac{d}{dB_1} [-aE[x] + \frac{1}{2} a^2 \cdot \sigma_x^2] = 0 \]

\[ \Rightarrow \frac{1}{a} \cdot e^{-aE[x]} + \frac{1}{a} a^2 \cdot \sigma_x^2 \cdot [-a \ell_2 \cdot (w_1 \cdot g_1 \cdot f'_1(B_1) - w_2 \cdot g_2 \cdot f'_2(B - B_1)) \]

\[ + 2 \cdot E[\eta_1 - 1] \cdot w_1 \cdot g_c \cdot f'_c(B_1) + e^{-\beta} \cdot (w_1 \cdot g_1 \cdot f'_1(B_1) \cdot 2^{-(\gamma_1 + \mu_2)} \]

\[ - w_2 \cdot g_2 \cdot f'_2(B - B_1) \cdot 2^{-(\gamma_2 + \mu_1)} + 2 \cdot E[\eta_1 - 1] \cdot w_1 \cdot f'_c(B_1) \cdot 2^{-(\gamma_1 + \mu_1)}) \]

\[ + \frac{a^2}{2} (e^{-2\beta} 4 \ell_2^2 \cdot \sigma_{\eta_1}^2 \cdot w_1^2 \cdot g_c^2 \cdot 2 \cdot f_c(B_1) \cdot f'_c(B_1) \]

\[ + e^{-4\beta} 4 \ell_2^2 \cdot w_1^2 \cdot g_c^2 \cdot \sigma_{\eta_1}^2 \cdot 2 \cdot f_c(B_1) \cdot f'_c(B_1) \cdot (2^{-(\gamma_1 + \mu_1)})^2) = 0 \]

\( \Rightarrow \) If we represent the above as \( A \cdot dZ = 0, \)

\( \text{then } dZ = 0 \text{ where } A = \frac{1}{a} e^{-aE[x]} + \frac{1}{2} a^2 \cdot \sigma_x^2 \)

\( \Rightarrow \) For the above equation to give the optimal value \( B_1^* \),

we need the SOC to satisfy \( \frac{\partial^2 L}{\partial B_1^2} \leq 0 \)

i.e.

\[ \frac{1}{a} \cdot e^{-aE[x]} + \frac{1}{a} a^2 \cdot \sigma_x^2 \cdot (dZ)^2 + \frac{1}{a} \cdot e^{-aE[x]} + \frac{1}{2} a^2 \cdot \sigma_x^2 \cdot \frac{d}{dB_1} dZ \leq 0 \]

i.e.

\[ \frac{a}{2} e^{-2\beta} 4 \ell_2^2 \cdot \sigma_{\eta_1}^2 \cdot w_1^2 \cdot g_c^2 \cdot (2 \cdot f_c(B_1) \cdot f''_c(B_1) + 2 \cdot (f'_c(B_1))^2) \cdot (1 + e^{-2\beta} (2^{-(\gamma_1 + \mu_1)})^2) \]

\[ \leq a e^{-\beta} \ell_2 \cdot (w_1 \cdot g_1 \cdot f''_1(B_1) + w_2 \cdot g_2 \cdot f''_2(B - B_1) + 2 \cdot E[\eta_1 - 1] \cdot w_1 \cdot g_c \cdot f''_c(B_1) \]

\[ + e^{-\beta} \cdot (w_1 \cdot g_1 \cdot f''_1(B_1) \cdot 2^{-(\gamma_1 + \mu_2)} \]

\[ + w_2 \cdot g_2 \cdot f''_2(B - B_1) \cdot 2^{-(\gamma_2 + \mu_1)} + 2 \cdot E[\eta_1 - 1] \cdot w_1 \cdot f''_c(B_1) \cdot 2^{-(\gamma_1 + \mu_1)}) \]

Now applying the envelope theorem to the FOC, we get

\[ \left[ A \cdot (dZ)^2 + A \cdot \frac{d}{dB_1} dZ \right] \frac{dB_1}{d\sigma_{\eta_1}^2} = -A \cdot dZ \cdot \frac{dA}{d\sigma_{\eta_1}^2} - A \cdot \frac{d}{d\sigma_{\eta_1}^2} dZ \]
\[
\frac{dB_1}{d\sigma_{\eta_1}^2} = \frac{-d}{d\sigma_{\eta_1}^2} dZ \\
\frac{dB_2}{d\sigma_{\eta_2}^2} = \frac{d}{d\sigma_{\eta_2}^2} dZ
\]

Now \[
\frac{d}{d\sigma_{\eta_1}^2} dZ = \frac{a^2}{2} e^{-2\beta} A.\ell_2. w_1. g_c. 2 f_c(B_1). f_c'(B_1). (1 + e^{-2\beta}. (2^{-(r_c+\mu_1)})^2) < 0
\]

and \[
\frac{d}{dB_1} dZ < 0 \quad \text{(to meet SOC to ensure that } B_1^* \text{ is utility maximizer)}
\]

\[
\Rightarrow \frac{dB_1}{d\sigma_{\eta_1}^2} < 0
\]

Similarly for the sequential offshoring case (from (4.2.4)), we obtain,
\[
\frac{dB_1}{d\sigma_{\eta_1}^2} < 0, \quad \frac{dB_2}{d\sigma_{\eta_2}^2} > 0, \quad \frac{dB_1}{d\sigma_{\eta_2}^2} < 0, \quad \frac{dB_2}{d\sigma_{\eta_2}^2} > 0 \quad \text{QED.}
\]

### B.9 Proof of Proposition 7:

We incorporate the definitions of \(\ell_2\) for the simultaneous case (using (4.2.1)) and analyze.

\[
x = B + e^{-\beta} (\ell_2 e^\left((\mu_2 - \frac{\sigma_2^2}{2}) + \sigma_2. z_1\right). \sum_n w_n. g_n. f_n(B_n)
\]

\[
+2. \ell_2 e^\left((\mu_2 - \frac{\sigma_2^2}{2}) + \sigma_2. z_1\right). c.g_c.f_1(B_1)
\]

\[
+e^{-2\beta} (\ell_2 e^\left(2(\mu_2 - \frac{\sigma_2^2}{2}) + \sigma_2. z_2\right). \sum_n w_n. g_n. 2^{-(r_n + \mu_n)} f_n(B_n)
\]

\[
+2. \ell_2 e^\left(2(\mu_2 - \frac{\sigma_2^2}{2}) + \sigma_2. z_2\right). c.g_c. 2^{-(r+\mu_1)} f_1(B_1)
\]

Taking the FOC (as in proof of Proposition 5) with respect to \(B_1\),

\[
U'(x). [\ell_2 e^\left((\mu_2 - \frac{\sigma_2^2}{2}) + \sigma_2. z_1\right). (w_1. g_1. f_1'(B_1) - w_2. g_2. f_2'(B - B_1) + 2.c.g_c. f_1'(B_1))
\]

\[
+\ell_2 e^{-\beta} e^\left(2(\mu_2 - \frac{\sigma_2^2}{2}) + \sigma_2. z_2\right). e^{-\beta} (w_1. g_1. f_1'(B_1). 2^{-(r_1 + \mu_2)}
\]

\[-w_2. g_2. f_2'(B - B_1). 2^{-(r+\mu_1)} + 2.c.g_c. f_1'(B_1). 2^{-(r+\mu_1)})] = 0
\]

Since the SOC conditions are satisfied, solution of the above gives \(B_1^*\) and hence \(B_2^*\).

Identifying the above FOC as \(U'(x). Z1 = 0\), we get \(Z1 = 0\) and

\[
\frac{dB_1}{d\sigma_{\eta_2}^2} = \frac{-U''(x). Z1. (dx/d\sigma_{\eta_2}^2) - U'(x). (dZ1/d\sigma_{\eta_2}^2)}{U''(x). (Z1)^2 + U'(x). (dZ1/dB_1)} = \frac{dZ1/d\sigma_{\eta_2}^2}{dZ1/dB_1}
\]
B.9. PROOF OF PROPOSITION 7:

Now \( \frac{dZ_1}{dB_1} < 0 \Rightarrow \text{sign} \left( \frac{dB_1}{d\sigma_{t_2}^2} \right) = \text{sign} \left( \frac{dZ_1}{d\sigma_{t_2}^2} \right) \) and

\[
\text{sign} \left( \frac{dZ_1}{d\sigma_{t_2}^2} \right) = \text{sign} \left( - \frac{z_1}{2.\sigma_{t_2}^2} \right) \left( \ell_{20}.e^{(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_1}.(w_1.g_1.f'_1(B_1) - w_2.g_2.f'_2(B - B_1)) \right)
\]

\[
+(-1 + \frac{z_2}{2.\sigma_{t_2}^2}).(\ell_{20}.e^{-\beta}.e^{2(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_2}.e^{-\beta}(w_1.g_1.f'_1(B_1).2^{-(r_1+\mu_2)})
\]

\[
-w_2.g_2.f'_2(B - B_1).2^{-(r_2+\mu_1)})\right) = \text{sign} \left( \frac{1}{2} \ell_{20}.e^{(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_1}.(w_1.g_1.f'_1(B_1) - w_2.g_2.f'_2(B - B_1)
\]

\[
+2.c.g_c.f'_1(B_1))\right)
\]

(from \( Z_1 = 0 \) and as \( z_t \sim N(0,t) \), \( E[z_1] = E[z_2] = 0 \)

\( \Rightarrow \frac{dB_1}{d\sigma_{t_2}^2} > 0 \) if \( f'_1(B_1)(w_1.g_1 + 2.c.g_c) > f'_2(B - B_1).w_2.g_2 \)

Similarly, applying \( \ell_{2t} \) for the sequential case (using (4.2.3)) and analyzing,

\[
x' = B_1 + e^{-\beta}.(B_2 + \ell_{20}.e^{(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_1}).w_1.g_1.f'_1(B_1) + \ell_1.w_2 + (1
\]

\[
+\ell_{20}.e^{(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_1}).c.g_c.f'_1(B_1))
\]

\[
+e^{-2\beta}.(\ell_{20}.e^{2(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_2}).w_1.g_1.f'_1(B_1).2^{-(r_1+\delta_1\mu_2)}
\]

\[
+\ell_{20}.e^{2(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_2}).w_2.g_2.f'_2(\nu.B_2).((1 + \epsilon)^{-\delta_2\mu_1}
\]

\[
+2.\ell_{20}.e^{2(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_2}).c.g_c.2^{-(r_c+\delta_1\mu_2)}f'_1(B_1))\right)
\]

Taking the FOC (as in proof of the simultaneous case) with respect to \( B_1 \),

\[
\frac{U'(x)\ell_{20}.e^{(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_1})(w_1.g_1.f'_1(B_1) + c.g_c.f'_1(B_1)) + \ell_1.c.g_c.f'_1(B_1)
\]

\[
+\ell_{20}.e^{-\beta}.e^{2(\mu_{t_2}-\frac{\sigma_{t_2}^2}{2})+\sigma_{t_2}.z_2}).(w_1.g_1.f'_1(B_1).2^{-(r_1+\delta_1\mu_2)}
\]

\[
-w_2.g_2.\nu.\ell_{20}.e^\beta.(B - B_1))(1 + \epsilon)^{-(\delta_2\mu_1) + 2.c.g_c.f'_1(B_1).2^{-(r_c+\delta_1\mu_1)}) = 0
\]

Since the SOC conditions are satisfied, solution of the above gives \( B_1^* \) and hence \( B_2^* \).

Identifying the above FOC as \( U'(x).Z2 = 0 \), we get \( Z2 = 0 \) and

\[
\text{Now} \frac{dZ_2}{dB_1} < 0 \Rightarrow \text{sign} \left( \frac{dB_1}{d\sigma_{t_2}^2} \right) = \text{sign} \left( \frac{dZ_2}{d\sigma_{t_2}^2} \right) \) and
PROOFS FOR STYLIZED MODELS

\[ \text{sign} \left( \frac{dZ_2}{d\sigma_{t_2}^2} \right) = \text{sign} \left( \ell_{20} e^{(\mu_{t_2} - \frac{\sigma_{t_2}^2}{2}) + \sigma_{t_2} z_{1}} \cdot (-\frac{1}{2} + \frac{z_1}{2\sigma_{t_2}}) \cdot (w_1 g_1 f_1'(B_1) + c g_{c1} f_1'(B_1)) \right) \]

\[ + \frac{e^{-\beta \cdot e^{(2(\mu_{t_2} - \frac{\sigma_{t_2}^2}{2}) + \sigma_{t_2} z_2)}}}{2} \cdot (w_1 g_1 f_1'(B_1) + c g_{c1} f_1'(B_1)) \cdot 2^{-(r_1 + \delta_{\mu_2})} \]

\[ - w_2 g_2 \cdot \nu \cdot f_2'(\nu \cdot e^{(B - \epsilon)} (1 + \epsilon)^{-\delta_{2\mu_1}} + 2 c g_{c2} f_2'(B_1) \cdot 2^{-(r_c + \delta_{1\mu_1}))} \]

\[ = \text{sign} \left( \ell_{20} e^{(\mu_{t_2} - \frac{\sigma_{t_2}^2}{2}) + \sigma_{t_2} z_{1}} \cdot \frac{1}{2} \cdot (w_1 g_1 f_1'(B_1) + c g_{c1} f_1'(B_1)) \right) \]

\[ + \text{sign} \left( \ell_{20} e^{(\mu_{t_2} - \frac{\sigma_{t_2}^2}{2}) + \sigma_{t_2} z_{1}} \cdot \frac{1}{2} \cdot (w_1 g_1 f_1'(B_1) + c g_{c1} f_1'(B_1)) \right) \]

\[ \text{(from } Z_2 = 0 \text{ and as } z_t \sim N(0, t), E[z_1] = E[z_2] = 0) \]

\[ \Rightarrow \frac{dB_1}{d\sigma_{t_2}^2} < 0 \]

Going through the same steps for \( \mu_{t_2} \), we see that \( \frac{dB_1}{d\mu_{t_2}} = 0 \) QED.
B.10 Supplementary: Two Stage Investment

Work Time: Compared to the work time explained in Chapter 4, here the efforts are spread over two time periods $t = 0$ and $t = 1$. Their respective impacts are experienced in time periods $t = 1$ and $t = 2$ and are shown in Fig B-1. The explanations for Fig B-1 follow the same as that for Fig 4-1 in Chapter 4 with some differences for time $t = 2$. The effort exerted (budget) for task $n$ is now $B_{0n}$ and $B_{1n}$ for time periods $t = 1$ and $t = 2$ respectively. The work time observed at $t = 1$ is as seen in Chapter 4.

![Figure B-1: Work time changes with offshoring](image)

In the next period $t = 2$, the learning by repeated doing effects $r_n$ and the effects of doing the other task $\mu_{-n}$ are observed as in Chapter 4. However the complete effects of the $t = 1$ efforts exerted $B_{1n}$ are not observed at $t = 2$ due to the overlap of some of these efforts and the effects of learning by doing $r_n$, and learning by doing something else $\mu_{-n}$. The work time is thus $w_n g_n 2^{-(r_n+\mu_{-n})} f_n(B_{0n} + h_n B_{1n})$, where $h_n = h_n(\mu_{-n}, r_n)$ is the overlapping effect. Also $0 \leq h_n(\mu_{-n}, r_n) \leq 1$ and $\frac{d h_n(\mu_{-n}, r_n)}{d \mu_{-n}} < 0$ and $\frac{d h_n(\mu_{-n}, r_n)}{d r_n} < 0$, $h_n$ is decreasing in $\mu_{-n}$ and $r_n$, i.e. with increased learning (by repeated doing or by doing something else) the effect of the efforts exerted in $t = 1$ (and hence realized in $t = 2$) is reduced.

Coordination Time: The coordination time $c$ also changes similar to work time. Coordination time is the maximum of the time required for coordination among the participating tasks, i.e. the coordination time of the task which requires more coordination time.

Thus, for $t = 1$, the coordination time is $c g_c \max_n(f_n(B_{0n}))$, where $g_c$ is similar to $g_n$, i.e. the increase in coordination time when both tasks are moved to the GPD location (we observed this during the course of our empirical example of the previous
section: the coordination efficiency between two tasks differed when both were co-located at the GPD location). Similarly, for \( t = 2 \), we get the coordination time as \( c.g_c \cdot \max_n(2^{-(r_n+\mu_n)} \cdot f_n(B_{0n} + B_{1n}, h_n(\mu_n, r_n))) \). We observe from the equations that the efforts \( B_{0n} \) and \( B_{1n} \) are being exerted on the tasks \( n \) to improve their deliverables (work and coordination time efficiencies). They help the respective tasks to recognize their interactions with and dependencies to the other task. This leads to better coordination and reduction in coordination time.

As shown/discussed above, the effect of the effort exerted at time \( t = 1 \) (effect observed in time period \( t = 2 \)) does not follow the curve of \( f_n(B_n) \) due to the interference effects of the learning effects (by repeated doing and by doing something else).

\subsection*{B.10.1 Supplementary}

Here we show how to solve the two stage problem.

**Problem Formulation:** Following the same steps as in Chapter 4, we now get the total costs as follows:

\[
x = B_0 + e^{-\beta}(B_1 + l_2 \sum_n w_n.g_n \cdot f_n(B_{0n}) + 2.l_2.(\eta_n - 1).w_n.g_c \cdot \max_n(f_n(B_{0n})))
\]

\[
+ e^{-2\beta}(l_2 \sum_n w_n.g_n \cdot 2^{-(r_n+\mu_n)} \cdot f_n(B_{0n} + B_{1n}, h_n(\mu_n, r_n))
\]

\[
+ 2.l_2.(\eta_n - 1).w_n.g_c \cdot \max_n(2^{-(r_n+\mu_n)} \cdot f_n(B_{0n} + B_{1n}, h_n(\mu_n, r_n))) 
\]

Our problem formulation is now:

\[
\text{Min } x \text{ subject to } B_0 \geq \sum_n B_{0n}; \quad B_1 \geq \sum_n B_{1n} \quad (B.10.2)
\]

**Solution:** We form the Lagrangean as follows:

\[
L(B_{0n}, B_{1n}, v_0, v_1) = x + v_0.(B_0 - \sum_n B_{0n}) + v_1.(B_1 - \sum_n B_{1n}) \quad \text{for } n = 1, 2 \quad (B.10.3)
\]

Continuing, from Chapter 4, with our assumption that there is no interior point solution (all budget is used), we have \( B_0 = B_{01} + B_{02}; B_1 = B_{11} + B_{12} \). Also, without loss of generality, let us assume that:

\[
\max(f_n(B_{0n})) = f_1(B_{01})
\]

\[
\max(2^{-(r_n+\mu_n)} \cdot f_n(B_{0n} + B_{1n}, h_n(\mu_n, r_n))) = 2^{-(r_{\mu_2}+\mu_2)} \cdot f_1(B_{01} + B_{11}, h_1(\mu_2, r_1))
\]

Our analysis shows that using different tasks in different periods for the max
function does not affect the comparative analysis results though it may change the solutions shown in the following sections marginally.

We replace the above assumptions in (B.10.1), (B.10.2) and (B.10.3) to obtain

\[
L(B_{01}, B_{11}) = x' \quad \text{where}
\]

\[
x' = B_0 + e^{-\beta} \cdot (B_1 + l_2 \cdot (w_1 \cdot g_1 \cdot f_1(B_{01}) + w_2 \cdot g_2 \cdot f_2(B_0 - B_{01}))
+ 2l_2 \cdot (\eta_1 - 1) \cdot w_1 \cdot g_c \cdot f_1(B_{01}))
+ e^{-2\beta} \cdot (l_2 \cdot w_1 \cdot g_1 \cdot 2^{-(r_1 + \mu_2)} \cdot f_1(B_{01} + B_{11} \cdot h_1(\mu_2, r_1))
+ l_2 \cdot w_2 \cdot g_2 \cdot 2^{-(r_2 + \mu_1)} \cdot f_2(B_0 - B_{01} + (B_1 - B_{11}) \cdot h_2(\mu_1, r_2))
+ 2l_2 \cdot (\eta_1 - 1) \cdot w_1 \cdot g_c \cdot 2^{-(r_c + \mu_2)} \cdot f_1(B_{01} + B_{11} \cdot h_1(\mu_2, r_1)))
\]

We solve for \( B_{01} \) and \( B_{11} \) using the first order conditions \( \frac{\partial L}{\partial B_{01}} = 0 \) and \( \frac{\partial L}{\partial B_{11}} = 0 \). We use the second order conditions to obtain the Hessian \( H = \frac{\partial^2 L}{\partial B_{01} \partial B_{11}} = \frac{(\partial^2 L)}{\partial B_{01} \partial B_{11}}^2 \) . As the Hessian \( H \geq 0 \), the solution to the first order equations gives the minima conditions. The solutions from the first order conditions (similar to Loch & Kavadias (2002)) are:

\[
\frac{f'_1(B_{01} + B_{11} \cdot h_1(\mu_2, r_1))}{f'_2(B_0 - B_{01} + (B_1 - B_{11}) \cdot h_2(\mu_1, r_2))} = \frac{w_2 \cdot g_2 \cdot 2^{-(r_2 + \mu_1)} \cdot h_2(\mu_1, r_2)}{w_1 \cdot h_1(\mu_2, r_1) \cdot (g_1 \cdot 2^{-(r_1 + \mu_2)} + 2 \cdot g_c \cdot (\eta_1 - 1) \cdot 2^{-(r_c + \mu_2)})}
\]

and

\[
e^{-\beta} \cdot (g_1 \cdot 2^{-(r_1 + \mu_2)} + 2 \cdot g_c \cdot (\eta_1 - 1) \cdot 2^{-(r_c + \mu_2)} \cdot w_1 \cdot (1 - \frac{h_1(\mu_2, r_1)}{h_2(\mu_1, r_2)}) \cdot f'_1(B_{01} + B_{11} \cdot h_1(\mu_2, r_1)) + (g_1 + 2 \cdot g_c \cdot (\eta_1 - 1) \cdot w_1 \cdot f'_1(B_{01}) - g_2 \cdot w_2 \cdot f'_2(B_0 - B_{01}) = 0
\]

We get a system of two equations in two variables and this can be solved using numerical methods. Also, this solution is similar to a dynamic program wherein an input (here effort) at time \( t=0 \) has a stochastic output \( f_1(B_{01}) \) at time \( t=1 \), and the effort input at time \( t=1 \) is based on the observed output at \( t=1 \). Solution to this dynamic program can be obtained by starting from the \( t=2 \) conditions given by (B.10.6) and then proceeding backwards to the \( t=1 \) conditions (given by (B.10.7)). This approach can be extended to \( n \) tasks and \( t \) time periods \( (n, t \text{ finite}) \) with (B.10.6) as the \( t \) period condition and using (B.10.7) conditions for the earlier periods (similar to Loch & Kavadias (2002)).
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