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Anshuman Tripathy, Steven D. Eppinger

Institutions: Indian Institute of Management Ahmedabad, Massachusetts Institute of Technology

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Structuring Work Distribution for Global Product Development Organizations

Anshuman Tripathy
Indian Institute of Management, Bannerghatta Road, Bangalore, India, atripathy@iimb.ernet.in

Steven D. Eppinger
Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Massachusetts USA, eppinger@mit.edu

This study describes (through an application) a novel approach toward organizing work distribution across globally distributed design and development centers of a product development (PD) organization. While there exist several studies (and modeling applications) for work distribution and allocation for manufacturing and supply chain networks, those related to product development organizations are limited to qualitative suggestions such as offshoring of modular tasks. However, most PD efforts are characterized by significant complexity in information sharing and information dependency among PD tasks (represented by coupling in the system architecture of the firm), thus preventing the identification of modular tasks. Also, redesigning the architecture to introduce modularity has associated risks of costs and product integrity. We demonstrate a methodology to organize work distribution globally in an industrial setting, utilizing the design structure matrix to quantify the system architecture of the firm. Our optimization results show significant cost savings through a restructured PD organization. On analysis of the results, we make two significant observations: (a) while offshoring based on modularity is generally appropriate, 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; and (b) firms should successively increase work allocation to the offshore location, benefiting from capability improvements through learning effects.

Key words: distributed product development; complex engineered systems; system architecture; design structure matrix
History: Received: November 2010; Accepted: May 2012 by E.G. Anderson Jr. and G.P. Parker, after 1 revision

1. Introduction and Motivation

Nokia, a Finland-based corporation, is involved in the design, development, manufacture, and sale of mobile phones, smart phones, and related services. Their product line has evolved from the mobile phones of the 1990s to include many more features and significant associated services (http://www.nokia.com/about-nokia/company/story-of-nokia). Fierce global competition in Nokia's key markets has brought about a number of challenges for the company, including how to maintain and improve efficiency of their global engineering organization. The product development (PD) activities of Nokia's High-End Devices Division (NHEDD) are performed by various departments (Nokia requested, for confidentiality, that the names of the departments and the division be changed, the data scaled, and that the results discuss sample cases). Each department carries out specific PD tasks, either solely or in collaboration with other departments, toward fulfilling its PD responsibilities. The PD activities of the firm were spread over six locations globally. The firm had been performing PD tasks at five of these locations for many years, and the sixth location (hereafter referred to as the GPD location) was in its third year of operations. The GPD location was significantly distanced from the other locations. Each department was performing PD activities at multiple locations. The existing distribution and spread of PD responsibilities across the locations posed significant challenges to the firm toward PD performance. As they explored expanding their operations at the GPD location, NHEDD wanted to structure the global distribution of PD work, optimizing for best cost efficiencies.

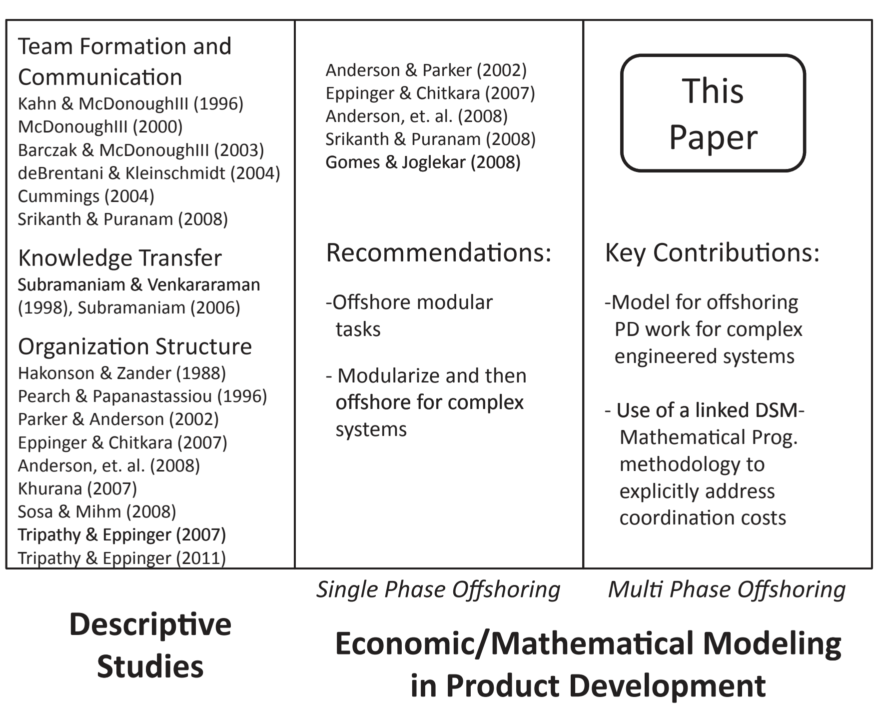
NHEDD's problem is similar to that faced by many firms that are trying to engage in global product development (GPD), in particular those that are involved in the design and development of complex products and systems. Competitive pressures (pricing targets driving aggressive cost targets), availability of exceptional talent overseas, advances in communication tools, intellectual property protection, and growing external markets are some factors that are influencing the drive toward GPD (Eppinger and Chitkara 2007).

GPD refers to the organizational arrangement that a firm adopts. This arrangement outlines, at a time epoch or dynamically, the location and ownership for each PD activity (Anderson et al. 2008, Eppinger and Chitkara 2007). The location of these activities (either whole or part) may be at a central location or distributed over various locations (referred to as offshore locations when separated by significant distances in time-zones, culture, geography, etc.). Developing products across such distances challenges the information/exchange requirements between PD activities that happen in parallel but are conducted in different locations (Fine 1998, Srikanth and Puranam 2011). Such information/exchange is required to ensure successful integration of PD work knowledge toward product development. Parker and Anderson (in press) define knowledge work integration as "the operation of all organizational mechanisms across organization and task boundaries that, alone or in concert, maintain the integrity of the distributed project's vision and its quality from project initiation to customer delivery."

Firms practicing GPD face the onerous challenge of identifying the PD content that will be offshored. Identifying this content could be mathematically complex (Anderson and Joglekar 2005), or lie on a rugged landscape (Levinthal 1997), or be similarly complex. The problem faced by NHEDD is a special case of this problem wherein an existing distribution needed to be reviewed for optimal distribution of PD effort. These types of problems have been well addressed for globally distributed manufacturing and supply chain networks where the key trade-off relates to the relative manufacturing and logistics costs. However, such studies do not exist, to the best of our knowledge, for distributed product development (please refer to Parker and Anderson, in press, for an extensive survey of literature related to integration decisions in distributed knowledge work). Existing studies listed in Figure 1 have been primarily descriptive, providing qualitative prescriptions. Economic/mathematical modeling studies in distributed product development (though suggested by a few) have not been attempted. This study looks at GPD organizations using economic modeling for complex systems for multi-phase offshoring. Thus the methodology adopted in this study can be extended to simple systems and single-phase offshoring.

Modularity, "a plan for organizing work by task partitioning (von Hippel 1990) and specifying standardized interfaces (Baldwin and Clark 2000, Fujimoto 2002) between them" (Srikanth and Puranam 2011), has been proposed as an approach to identify the offshore content (Anderson et al. 2008). However, for complex engineered systems (CES) it is generally not possible to identify highly modular work during the design and development stages (though it may be possible to identify modular components during the manufacturing and supply chain stages). We believe that this is a key reason why there is limited use of mathematical models in PD work distribution studies so far. To that extent, our study outlining a methodology to incorporate mathematical programming in complex systems represents an innovative attempt.

Figure 1 Current Literature Status in Offshoring of Product Development Content



CES, such as the mechatronics systems designed and developed by Nokia for automobiles, aircraft, etc. have significant interaction requirements between the various components/tasks across sub-sytems in non-simple ways (Whitney et al. 2004) (as shown in Figure 2). The interaction requirements are identified by the system architecture (Rechtin and Maier 2000). These interaction requirements often make it difficult to decompose a complex system into modules (Ethiraj and Levinthal 2004, Sosa et al. 2007) that may be offshored. However the firm may have strong motivations for having distributed PD resources. This makes it difficult to manage the coordination requirements across locations such that product integration is neither interrupted nor challenged. Thus it becomes necessary to identify the organization (work distribution) to efficiently manage these coordination needs. We use a methodology that adopts the design structure matrix (DSM) (Eppinger et al. 1994, Steward 1981) to identify these coordination needs, and through a set of DSM transformations develop the data needs of the mathematical program. Our approach for collecting coordination data, collating it, and its subsequent use in a linked DSM-Mathematical Programming methodology is a unique contribution of this study. This method can be used, with suitable adjustments, by practitioners in the design of their respective distributed development organizations. It can also be used by academics to further analyze issues related to product development organization design and coordination costs.

We build on extant literature, in section 2, to develop a general recursive equation to design an efficient globally distributed product development organization. In section 3, we outline a methodology to structure the PD organization, using the case study of NHEDD. We observe significant cost saving opportunities through a timed restructuring of the PD organization. In section 4 we discuss our proposed methodology and the challenges in implementing the same elsewhere. We conclude thereafter.

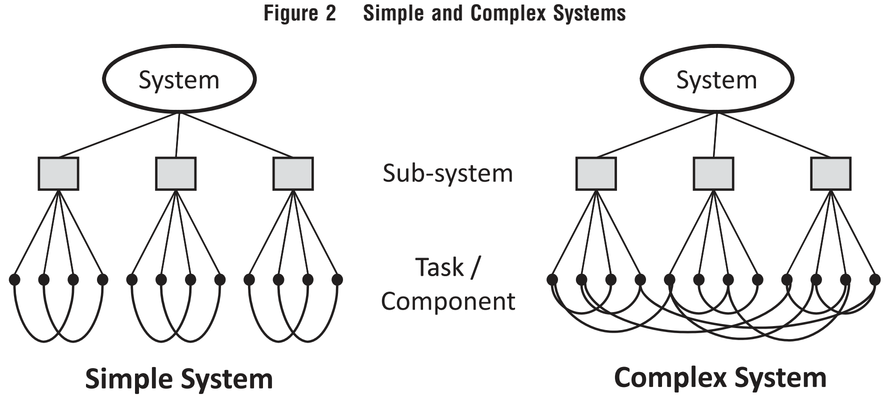
2. Modeling Global Product Development

As outlined by Kuemmerle (1997), firms pursue GPD to either meet offshore market needs (home base exploiting) or to enhance their overall PD performance (home base augmenting). Firms augment their existing PD performance in various ways through GPD: pursue PD offshoring at low manpower rate locations, thereby reducing overall costs; identify competencies in specific PD process areas that are available at offshore locations; or develop overseas PD locations as hedging opportunities for standard PD work. In this section, we develop the model for a firm pursuing GPD for cost efficiencies. This model can be extended for firms that pursue GPD seeking competencies and hedging opportunities.

Gomes and Joglekar (2008) identified two streams of literature to classify the criteria for offshoring PD tasks: the information processing (IP) view and the transactions cost (TC) theory. Both streams are concerned with successful product development per the cost, time, and quality objectives of the firm. The IP view of product development posits that success is adversely impacted as the distance between the groups that need to coordinate increases (Allen 1977, Sosa et al. 2002), the precise challenge in GPD organizations. The proposed countermeasure in such cases is either through offshoring of modular tasks (Baldwin and Clark 2000, Parker and Anderson 2002, Sanchez and Mahoney 1996) or through "task-partitioning" to ensure minimum interdependence across barriers (von Hipel 1990). If that is not possible, then it is recommended to improve the information and communication tools used for coordination (Kraut et al. 2002).

TC theory (Coase 1937, Williamson 1975), developed for firm boundaries, aims at reducing the total cost. Total cost has been summarized by Clemons et al. (1993) as

Figure 2 Simple and Complex Systems



$$\begin{aligned} &\textit{total cost} = \textit{production cost} + \textit{transaction cost} \\ &\textit{transaction cost} = \textit{coordination cost} \\ &\quad + \textit{operations risk} + \textit{opportunism risk}. \end{aligned} \tag{1}$$

Operations risk arises from environmental uncertainty and opportunism risk from behavioral uncertainty. We do not consider opportunism risk in Equation (1) for reorganization within the firm. Coordination costs are incurred during interactions across locations, and operations risk arises from environmental uncertainty relating to offshoring the PD task. This uncertainty leads to efficiency differences between various locations while performing the same tasks.

Building on the above streams, Gomes and Joglekar (2008) identified the coordination needs between the tasks that are offshored and those that are not as the key factor that drives the success of GPD organizations. Higher coordination needs imply more task interdependence. Modularity is a measure of task interdependence for a given architecture, indicating the "dis-connectivity" of a task from other tasks. We next incorporate the coordination needs in modeling a GPD organization and in defining a related measure for modularity.

2.1. Definitions

As discussed above, the need for coordination is the key factor to be incorporated for modeling GPD organization structures, and modularity a key measure for analyzing the same.

Brown and Eisenhardt (1995) state that PD comprises a set of disciplined problem solving tasks. Following Gomes and Joglekar (2008) we interpret "disciplined problem solving" to imply that PD comprises a set of information processing tasks in each of which information is received, generated, processed, and disseminated. This follows the information processing view of product development (Clark and Fujimoto 1991, Galbraith 1973, Parker and Anderson 2002, Tushman and Nadler 1978). Thus, the associated PD task time comprises time required for each of these activities related to processing of information. We segregate this task time into work time and coordination time. *Work time* is the time spent individually by the responsible group in performing the sub-tasks leading to the deliverables of the task. *Coordination time* is the time spent by the group in obtaining information to support its efforts, working jointly with other groups toward completing the deliverables of its tasks, disseminating the output of its tasks to other appropriate groups, etc. (receiving and disseminating information). Thus,

$$\textit{task time} = \textit{work time} + \textit{coordination time}.$$

This information (the division of *task time*) is obtained through system architecture studies. Operations risk (as shown in Equation (1)) is inherent in both work time and coordination time, as the time required to perform the same PD task may differ by the location where it is being done (both work time and coordination time are location dependent).

Applying the definition of modularity as an indicator of "dis-connectivity" (Anderson and Parker 2002, Gomes and Joglekar 2008) and the above segregation of task time, we identify an index for the modularity of a task in the GPD context as follows:

$$\textit{index of modularity},\ \frac{1}{\eta} = \frac{\textit{work time}}{\textit{work time} + \textit{coordination time}}. \tag{2}$$

Thus, a task that has low coordination requirements (in proportion to its work time) is more modular, and its index of modularity will tend toward 1. The modularity of a task reduces as its value decreases from 1. We use this measure of modularity in the rest of this article.

2.2. Model Setup

Consider a firm engaged in the design and development of a CES. The CES comprises 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 2012). We represent each of these component–activity combinations as a task n. The set of all tasks can be partitioned into two sets I and I', where I comprises of all n that the firm has identified for offshoring. I' is the set of tasks that the firm has decided against offshoring (intellectual property concerns, protection of core competence, lack of appropriate skills at the offshore location, etc.). Let k denote the locations where $n \in I$ can be carried out (current home, offshore locations, other onshore locations, etc.). A_{nkt} is the decision variable that indicates that task n is performed at location k at time t ($A_{nkt} \in \{0, 1\}$). We can then model the evolving GPD organization, with total cost as the value proposition and V_t as the total expected value at time t, as

$$V_t = \min_{A_{nkt}} \left[\left(S_t + \sum_k \sum_n \ell_{kt} \cdot A_{nkt} \cdot (w_{nkt} + c_{nkt}) \right) + e^{-\beta} \cdot E[V_{t+1}] \right]. \tag{3}$$

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' are located (with which it has to coordinate for successful completion of its tasks). Thus if we designate the home location as $k = 1$, an efficiency factor would be needed to relate w_{nkt} with the home location time $w_{n(k=1)t}$. Similarly we can have efficiency factors for the coordination time. We incorporate such efficiency factors in our application at NHEDD (Section 3.2).

ℓ_{kt} is the manpower rate at location k at time t. Costs are incurred when the organizational arrangement (work distribution) changes between time periods. These costs could correspond to the costs of hiring relevant engineers (and training them) or retrenching engineers etc. and would depend on the locations where the organizational arrangements change, the type of organizational change, etc. S_t represents the sum of all such costs (also known as switching costs) that correspond to the changes in the organizational arrangement between time periods $t-1$ and t. In the next section, we show how these costs are to be considered (in the example of NHEDD division). $e^{-\beta}$ is the discounting factor. The expectation on V_{t+1} 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 (and work assignments) to minimize the total cost over the period under study. Equation (3) is very general, and we do not specify any form to the data, that is S_t, ℓ_{kt}, w_{nkt}, etc. The form (linear, convex, step-wise linear, etc.) would be provided by the specific instance of use.

Some related constraints that may occur when Equation (3) is used are

$$\sum_k A_{nkt} = 1 \quad \forall i, j, t \tag{4}$$

$$c_{nkt} = \sum_{n'k'} c_{(n,k)(n',k')t} \quad \forall (n,k), (n',k'), t \tag{5}$$

$$\textit{other applicable constraints.} \tag{6}$$

Equation (4) ensures that each n is performed at a single location at time t. Thus it is equivalent to the work location problem seen in optimization literature (since we specified $A_{nkt} \in \{0,1\}$). The above formulation can be generalized to a work distribution problem by taking $A_{nkt} \in [0,1]$, that is, A_{nkt} is continuous in [0,1]. Equation (5) defines the total coordination time of n at location k at time t. The coordination time also depends on the location k' of all other n' with whom n has to coordinate.

This formulation is very general. It can be used to identify work allocation/distribution when a new offshore development center is being set up or when seeking a more efficient PD organization structure. Solving this formulation for CES is non-trivial due to non-separability of the characteristics of any task. Reassigning the work distribution of any task n across different locations affects its coordination time with all other tasks n', also depending on the locations k' of these n'. The key challenges when solving such a problem relate to (a) identifying and collating the appropriate data (the inter-dependencies), and (b) managing the complexity and non-linearity in the problem.

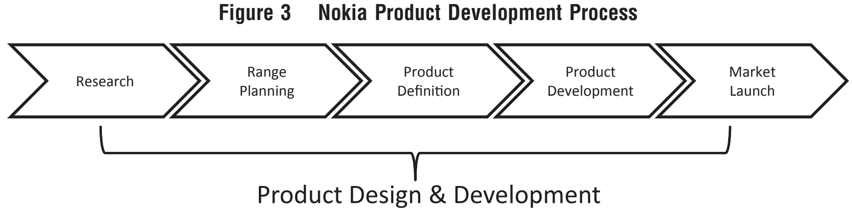
3. Problem Setting at Nokia and Results

NHEDD comprises the Hardware (A) and Software (B) business units. Various departments constitute these business units. We distinguish these departments between those that were flexible to reorganization (j) and those that were not (d). Business unit A had 10 j and a single d department. Business unit B comprised a single d department. The d departments also need to be considered due to the coordination needs between the respective departments.

The initial expansion of NHEDD beyond Finland (k = 1), the home location, was in search of competencies and development capacity. This led to development centers at various global locations (k = 2,3,4,5). With the evolution of the Internet and development of digital design tools, NHEDD set up another development center (k = 6, the low cost location), transferring the work responsibility of certain 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, NHEDD continued to face significant difficulties in managing development activities within the new center and between the new center and other development centers. NHEDD was looking at reorganizing the work distribution of the various departments across locations with an intent to minimize the total costs. A planning period of 5 years was to be considered.

PDD Process. NHEDD is involved in many programs simultaneously. NHEDD's product design and development (PDD) process (Figure 3) comprises

Figure 3 Nokia Product Development Process



range planning, product definition, and product development phases. The range planning phase is calendar based and common across products. This phase ends in December (year t) with the confirmed launch plans (including resource scheduling) for year $t + 2$ programs. 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 the total e are maintained constant by NHEDD for planning and execution purposes. Each product program type has defined time periods and manpower allocation for each phase, and within the product development phase, for each stage gate. The product 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 the range planning phase and start of the product definition phase. The product development phase starts on completion of product definition and ends when the product is ready for market launch, where the product is customized for respective market needs. Our study involved range planning, product definition, and product development phases. While there exist several formal and informal reviews during the various phases of PDD, the product development phase uses the the stage-gate process (Cooper 1993).

NHEDD was looking at optimizing 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 every year. Thus, in a hierarchical sense (Anderson and Joglekar 2005), we were looking at identifying the work distribution at a "strategic → operational" level; with the relevant constraints (Equation (6)) defined at the strategic level, and Equation (3) appropriately modified and solved at the operational level. Actual work distribution for each program would be based on simulation studies/manpower availability and would constitute the "tactical" level. At the aggregate planning level, the average coordination required by each type of program (coordination by plan; March and Simon 1958) is considered. Uncertainty is related to the specific nuances of each program, leading to unplanned coordination (coordination by feedback; March and Simon 1958), perhaps requiring temporary allocation of extra work time and coordination time, which are balanced by transferring engineering staff from other programs or by hiring temporary staff. Since we were to consider a planning period of 5 years, we needed a multi-period mathematical programming (deterministic) formulation of Equation (3).

Data Needs. Per Equation (3), we needed to segregate the task time between work time and coordination time. To the best of our knowledge, no firm measures this segregation (Thomke 2002 is an example where coordination cost [% of total effort] is identified as cost of travel, meetings, teleconferences, etc. that the headquarters incurs to support respective development centers, but it does not look at coordination for offshore development centers). We felt that performing this segregation with the available manpower allocation data at the phase/stage-gate level could lead to a number of assumptions and related approximations. For a more firm segregation of the task time into work time and coordination time, this segregation had to be done at the activity level instead so that the respective departments could identify the tasks that they are responsible for and other departments that they needed to coordinate with for these tasks. Such system architecture studies are usually performed to understand the relationships between entities performing various tasks (Whitney et al. 2004), particularly for organizations that are involved in CES (our area of interest).

Rechtin and Maier (2000) define system architecting as the art and science of creating and building complex systems, the part of systems development that is most concerned with scoping, structuring, and certification. The complexity of a system is defined by the complexity of the interconnections 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. Thus the architecture of the system identifies the coordination requirements between the components and the process tasks of a system, helping to segregate between work time and coordination time. We needed to quantify the system architecture of NHEDD. We also needed to identify the current work distribution (by department, by location) of NHEDD.

3.1. Quantifying the System Architecture

The foundation of NHEDD's PDD process is based on well-identified deliverables for each phase/stage gate. Each department performs, solely or in collaboration with other departments, a set of tasks to meet their respective deliverables, and there exist information flows/dependencies between these tasks across departments (Amaral et al. 2011). The system architecture (process flow) identifies these dependencies, and has to be done at the activity level for accuracy. We used a process-flow DSM (design structure matrix) to outline these tasks and the respective dependencies. DSM (Eppinger et al. 1994, Steward 1981) is a useful tool to decompose the architecture of a system, either by product, process, team/group, hybrid of these, or other things. It is a project modeling tool which represents the relationships between project tasks or sub-systems/components in a matrix form. We used a series of interviews to develop and quantify the DSM (the Delphi method could also be used, Gomes and Joglekar 2006 used personal structured interviews in their collection of coordination data).

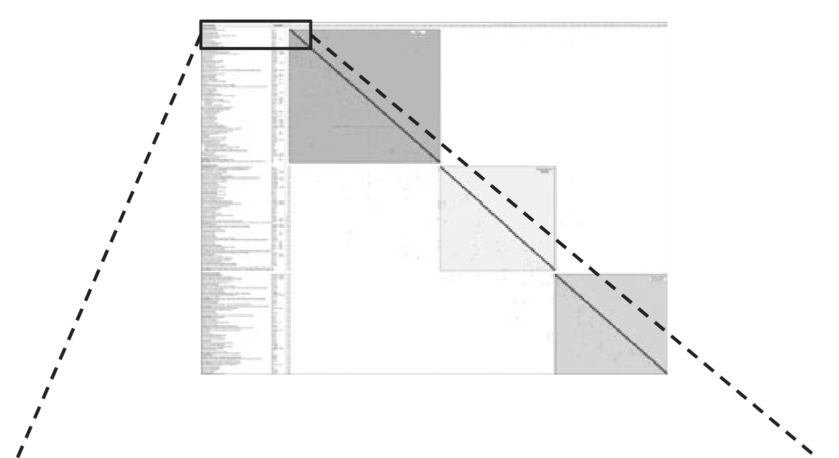
NHEDD identified a number of personnel from various departments for us to interview. We had two rounds of interviews, split by a month in between. In the first round (unstructured interviews), we interviewed 15 people (across different departments and the planning group) for 60–120 minutes each. Each of them had experience with many projects within their own department and had been involved in manpower planing and allocation. We asked them to identify the deliverables of their respective departments for each phase/stage gate and the tasks (i) required to be performed 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. The department responsible for each task was identified. In certain cases multiple departments were assigned 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: seven personal interviews of approximately 60 minutes each, group interviews (where we found significant dependencies between departments) of approximately 12 hours and a final full-day workshop. Based on these interviews and the workshop, we developed a modified process flow DSM (Figure 4) comprising 214 tasks. Ninety of these tasks required significant interactions between departments or had to be done jointly. The DSM had a total of 598 marks (dependencies), that is, approximately 2.79 dependencies per task.

Our next step involved connecting the process flow DSM (Figure 4) and the NHEDD data on manpower allocation. We met with representatives from the respective departments and those from the planning group and asked them to assign the manpower time allocation (assuming that all manpower is based at the home location $k = 1$) between the various tasks that the department is involved in in each phase/stage gate; and, for each task, to distribute the task time between work time and coordination time whenever multiple departments were involved for the tasks (Figure 5). The definitions for work time and coordination time given were as explained in section 2. Delays in obtaining information from the previous activity were to be considered as part of coordination time if the activity receiving the information included the department that was also responsible for providing the information; otherwise they were to be considered as part of the work time of the department that was receiving the information.

The split of task time to work time (w_{ij}) and coordination time ($c_{ijj'}$, c_{ijd}, $c_{idd'}$) data were developed by

Figure 4 Process DSM for Nokia High-End Devices Division PDD Process



Activity/Information	Responsibility		i	1	2	3	4	5	6
<u>Range Planning Phase</u>									
Range vision (gives planning targets)	A-PfM		1						
Approval of range vision	Bus		2	x					
Range program plan ready	A-PfM		3		x				
Consumer/market research (including operator inputs)	A-PfM		4						
B and SCD roadmaps (intent)	B-PfM		5		x				
Experience brief	A-PfM	B-PfM	6		x		x		

Figure 5 Example of Work Time and Coordination Time for PDD Process Tasks (Units: Man-Years)

		Category 1: Complex Products					Category 2: Standard Products				
Activity / Information	i↓	(j,k)	w_{ijk}	(j,k)'	$w_{i(jk)'}$	$c_{i(jk)(jk)'}$	(j,k)	w_{ijk}	(j,k)'	$w_{i(jk)'}$	$c_{i(jk)(jk)'}$
Architecture impact per requirement	64	BusM									
Implementation requirements for architecture changes	65	BusM									
Visibility on product's SW release, API usage	66	BusM									
Prepare SW architecture template for product families and products	67	A-AM	1.5								
Approved release plan	68	PRPF									
Range business plan	69	A-PfM	1	B-PfM		1					
Business and capability simulations	70	A-PfM	1	B-PfM		1					
Roadmapping milestone (PET)	71	Bus									
RM Milestone: Range planning completed for 200X	72	Bus		Bus-BP							
SRM milestone: *System Concepting Initiation:* cycle portfolio plan (freeze), resource releasing, start concepting different alternatives, business and system abstract is ready	73	B									
Product Planning Phase											
CS0 Milestone: Release resources for start of concepting different alternatives	74	A					A				
Architecture (DeSW, PC, Service)compliancy check against agreed API set	75	B-AM					B-AM				
Technology updates required/roadmap	76	B-AM		A-TM	0.7	0.35	B-AM		A-TM	0.3	0.2
Gap identification, recovery plan defined	77	A-PfM	0.2	A-R&D	0.1	0.3	A-PfM	0.18	A-R&D	0.1	0.15
Approved system design studies	78	A-AM	0.5				A-AM	0.2			
Identification of technical roadmap requirements	79	A-TM	2				A-TM	0.85			
Architecture study and API availability check and approval (API: application interface in sw)	80	A-R&D	0.1	A-AM	0.7	0.3	A-R&D	0.04	A-AM	0.35	0.15
Review architecture compliance to requirements	81	A-RM	1.35				A-RM	0.7			
Check design compliance to architectures	82	A-R&D	0.25	A-AM	0.6	0.3	A-R&D	0.04	A-AM	0.35	0.15
Product concept pre-studies (continues)	83	A-R&D	0.1	A-RM	0.55	0.15	A-R&D	0.08	A-RM	0.15	0.05

Figure 6 Organization (Department) nDSM (Units: Man-Years)

Dept.	A-AM	A-TM	A-RM	A-PgM	A-R&D	A-M	A-ID	A-UI	A-PM	A-OL	A-PfM	B	Index of Modularity	Modularity Rank
A-AM	20.63				6.89	1.67						4.29	0.6164	9
A-TM		33.29	0.23		5.18						0.31	0.76	0.8371	2
A-RM		0.23	65.78		8.75				4.34			0.33	0.8281	3
A-PgM				36.40	0.31				5.60	4.06		0.25	0.7807	4
A-R&D	6.89	5.18	8.75	0.31	139.40	8.67	1.25	12.39	10.63		0.39	11.75	0.6780	8
A-M	1.67				8.67	47.42	0.67	5.74			0.48	0.94	0.7231	6
A-ID					1.25	0.67	36.03		5.25			3.03	0.7795	5
A-UI					12.39	5.74		68.69	2.25			8.56	0.7036	7
A-PM			4.34	5.60	10.63		5.25	2.25	48.73		2.18	0.30	0.6147	10
A-OL				4.06						99.52		3.13	0.9326	1
A-PfM		0.31			0.39	0.48			2.18			0.29		
B	4.29	0.76	0.33	0.25	11.75	0.94	3.03	8.56	0.30	3.13	0.29			

the NHEDD's personnel based on their experience from various programs through the years. We resolved differences through a final full-day workshop. It was important to understand that $c_{ijj'} = \max(c_{ij}, c_{ij'})$, that is, coordination time is the maximum of the coordination time needed by the departments involved for successful completion of the task. Thus we had the average work time and the average coordination time split for the different programs of NHEDD. It is not necessary that every program followed this split exactly. We used this data to develop an organization (department) numerical DSM (nDSM) (Figure 6) from Figure 5 through an organization mapping exercise. We determined each department's work time as $w_j = \sum_i w_{ij}$ and coordination time with every other department as $c_{jj'} = \sum_i c_{ijj'}$ $(j \neq j')$ and $c_{jd} = \sum_i c_{ijd}$. This was done for each of the program types and then added with the respective number of programs of each type/year (a,b).

This nDSM (Figure 6) represents the architecture of NHEDD. It represents the work time w_j (along the diagonal) and coordination time (non-diagonal) split of the total task time for each department. The coordination time ($c_{jj'}$ and c_{jd}) is between a pair of departments. The departments are listed vertically and horizontally. 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. This nDSM is a square symmetric matrix (interactions between two departments is the same). Further, we also identified the index of modularity (per Equation (2)) of each j department, and identified the respective modularity ranks (ModRk) for each department.

3.2. Current Work Distribution of NHEDD

NHEDD's architecture (Figure 6) had been developed assuming that all the departments were co-located at the home location $k = 1$. To help us identify the current distribution of manpower across all locations for all departments, NHEDD provided us with m_{jk} and m_{dk} (m_{jk} representing the amount [%] of department j's work that was being done at location k, similarly for m_{dk}).

3.2.1. Efficiency Differences.

NHEDD had identified that there existed efficiency differences when departments carried out their respective tasks in different locations. There were two types of efficiencies: those that related to work time and those that related to coordination time. NHEDD had been collecting these data. We defined the work time efficiency as ϕ_{jk} for department j's tasks carried out at location k. The data were normalized with respect to $\phi_{j(k=1)}$, which is taken as 1.

The coordination efficiency differences $\theta_{kk'}$ between locations were also being experienced (ideally $\theta_{(jk),(j'k')}$ should be used, but data at such depth were not available). In discussions with NHEDD, we developed a matrix of relative coordination rankings (1–4) between and within locations. The highest ranking 1 took approximately half the time as that of the lowest ranking 4. Also, the time difference between rankings 1 and 2 was less than that between 2 and 3, which was less than that between 3 and 4. Thus it was convex increasing. We developed a convex function to provide a fit to these rankings with efficiency 1 for ranking 4 and efficiency 0.5 for ranking 1 (thus, concave decreasing function). These work time and coordination time efficiency factors corresponded to the current state ($t = 0$ time period) (Tripathy 2010).

3.2.2. Learning Effects.

Argote (1999), von Hippel and Tyre (1995) and others. have shown that there exist learning effects through repeated doing. NHEDD had been involved in product development in locations $k = 1,2,3,4,5$ over many years. Hence, measurable improvements in efficiency between successive time periods were not observable. However, for GPD location $k = 6$, learning effects were being experienced. We incorporated them through the respective efficiency factors:

$$\phi_{jk(T_k+t)} = \frac{\phi_{jk(T_k)}}{\left(\frac{T_k+t}{T_k}\right)^{-r_k}},$$

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

T_k in the above reflected the number of years that location k had been operating as a PDD center, and r_k is the learning rate at location k. We incorporated the above efficiency and learning factors in the system architecture at $k = 1$ (Figure 6) to identify the current ($t = 0$) manpower distribution for each department j,d at location k in the Work Distribution nDSM (Figure 7) using $w_{jk} = \frac{w_j \cdot m_{jk}}{\phi_{jk(t=0)}}$ and

$$c_{(jk)(j'k')(t=0)} = \frac{c_{jj'} \cdot m_{jk(t=0)} . m_{j'k'(t=0)}}{\theta_{kk'(t=0)}}.$$

Note: w_j and $c_{jj'}$ represent the architecture of NHEDD's PDD process (Figure 6). w_{jkt} and $c_{(jk)(j'k')t}$ represent the work allocation and are shown in Figure 7 for $t = 0$.

Summing across a row in Figure 7 gives the current manpower for a department j at location k. As a validation step, we checked this vis-a-vis existing manpower allocations (actuals) and found it to be comparable. Our objective now is to identify the Work Distribution (department and location) nDSM for time epochs $t = 1$ to $t = 5$. Our data development steps are summarized in Figure 8.

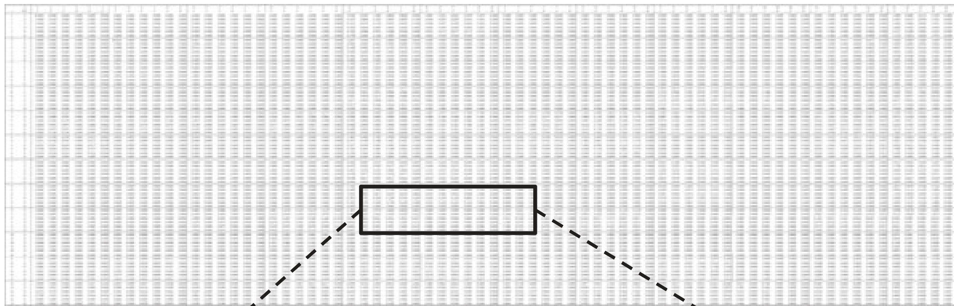
3.3. Problem Formulation

In Equation (3) A_{nkt} was the decision variable and w_{nkt} and c_{nkt} were the inputs. In NHEDD's case, we need to find the work allocation to optimize costs. This is similar to having $A_{nkt} \in (0, 1)$ in Equation (3). So we used w_{jkt}, $c_{(jk)(j'k')t}$ and $c_{(dk)(jk')t}$ as the decision variables, with their respective values at $t = 1$ as inputs.

3.3.1. Model.

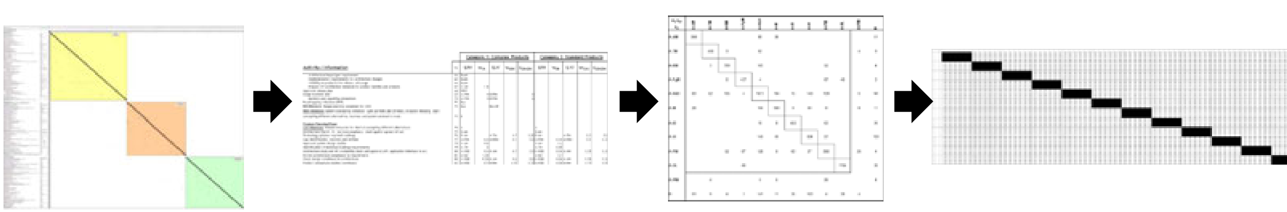
NHEDD's problem can now be formulated (specific case of Equation (3)) as:

Figure 7 Work Distribution (Department and Location) nDSM



	j'	4	4	4	4	4	4	5	5	5	5	5	5	6	6	6	6	6	6
j	k/k'	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
8	1	-	-	-	-	-	-	1.73	0.50	1.00	0.61	0.61	0.86	0.80	0.35	0.35	0.43	0.43	-
8	2	-	-	-	-	-	-	0.57	0.12	0.28	0.18	0.18	0.25	0.26	0.09	0.10	0.12	0.12	-
8	3	-	-	-	-	-	-	1.99	0.50	0.87	0.61	0.61	0.86	0.92	0.35	0.30	0.43	0.43	-
8	4	-	-	-	-	-	-	0.70	0.18	0.35	0.12	0.18	0.25	0.33	0.12	0.12	0.09	0.12	-
8	5	-	-	-	-	-	-	0.70	0.18	0.35	0.18	0.12	0.25	0.33	0.12	0.12	0.12	0.09	-
8	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	1	0.90	0.26	0.51	0.32	0.32	0.45	1.70	0.49	0.98	0.60	0.60	0.85	-	-	-	-	-	-
9	2	0.26	0.06	0.13	0.08	0.08	0.11	0.49	0.11	0.24	0.15	0.15	0.21	-	-	-	-	-	-
9	3	0.51	0.13	0.22	0.16	0.16	0.22	0.98	0.24	0.43	0.30	0.30	0.42	-	-	-	-	-	-
9	4	0.32	0.08	0.16	0.06	0.08	0.11	0.60	0.15	0.30	0.11	0.15	0.21	-	-	-	-	-	-
9	5	0.32	0.08	0.16	0.08	0.06	0.11	0.60	0.15	0.30	0.15	0.11	0.21	-	-	-	-	-	-
9	6	0.45	0.11	0.22	0.11	0.11	0.08	0.85	0.21	0.42	0.21	0.21	0.15	-	-	-	-	-	-

Figure 8 Data Development Methodology



$$\begin{aligned}
\textbf{Min} \sum_{t=1}^{5} e^{-\beta t} & \left(\sum_{k} \left(\sum_{j} (\ell_k \cdot (w_{jkt} + c_{jkt})) + \sum_{d} (\ell_k \cdot c_{dkt}) \right) \right) \\
& + \sum_{t=1}^{5} e^{-\beta(t-1)} \left(\sum_{k} SU_k \cdot \max \left(\left(\sum_{j} (w_{jkt} + c_{jkt} - w_{jk(t-1)} - c_{jk(t-1)}) + \sum_{d} (c_{dkt} - c_{dk(t-1)}) \right), 0 \right) \right) \\
& + \sum_{t=1}^{5} e^{-\beta t} \left(\sum_{k} SD_k \cdot \max \left(\left(\sum_{j} (w_{jk(t-1)} + c_{jk(t-1)} - w_{jkt} - c_{jkt}) + \sum_{d} (c_{dk(t-1)} - c_{dkt}) \right), 0 \right) \right) \\
& + \sum_{t=1}^{5} e^{-\beta t} \left(\sum_{k} \sum_{j} SUD_{jk} \cdot \max(w_{jkt} + c_{jkt} - w_{jk(t-1)} - c_{jk(t-1)}, 0) + \sum_{k} \sum_{d} SUD_{dk}. \max(c_{dkt} - c_{dk(t-1)}, 0) \right)
\end{aligned}$$

$$\textbf{s.t.} \sum_{j'} \sum_{k'} c_{(jk)(j'k')t} = c_{jkt} \quad \forall j,k,t \text{ and} \quad \sum_{j} \sum_{k'} c_{(dk)(jk')t} = c_{dkt} \quad \forall d,k,t \tag{7}$$

$$\sum_{k} w_{jkt} \times \phi_{jkt} \geq w_j \quad \forall j,t \tag{8}$$

$$\sum_{k} \sum_{k'} c_{(jk)(j'k')t} \times \theta_{kk't} \geq c_{jj'} \quad \forall j,j',t \quad \text{and} \quad \sum_{k} \sum_{k'} c_{(jk)(dk')t} \times \theta_{kk't} \geq c_{jd} \quad \forall j,d,t \tag{9}$$

$$\frac{\sum_{k'} (c_{(jk)(j'k')t} \times \theta_{kk't})}{w_{jkt} \times \phi_{jkt}} \geq \frac{c_{jj'}}{w_j} \quad \forall (jk),j',t \tag{10}$$

$$\frac{\sum_{k'} (c_{(jk)(dk')t} \times \theta_{kk't})}{w_{jkt} \times \phi_{jkt}} \geq \frac{c_{jd}}{w_j} \quad \forall (jk),d,t \tag{11}$$

$$\sum_{j} (w_{jkt} + c_{jkt}) + \sum_{d} c_{dkt} \leq \geq x * \left(\sum_{j} (w_{jk(t-1)} + c_{jk(t-1)}) + \sum_{d} c_{dk(t-1)} \right) \tag{12}$$

$$\textit{Non-negativity constraints} \tag{13}$$

The objective function (similar to Equation (3)) gives the total cost to be minimized over the planning horizon. Each of the four terms relates to a cost factor and has parts corresponding to j (flexible) and d (non-flexible) departments. The first term looks at the total manpower costs incurred in each period (with respective manpower rates ℓ_k): this corresponds to w_{nkt} and c_{nkt} in Equation (3). The next three terms correspond to the organization changes between successive periods (corresponding to S_t in Equation (3)), relating to the cost of hiring additional manpower at a location k (with corresponding rate SU_k), the cost of reducing manpower at a location k (SD_k), and the cost of increasing manpower for a department j/d at location k (SUD_{jk}), respectively.

Equations (7) are definition terms (similar to Equation (4)). Constraints (8) and (9) ensure that all the work time and coordination time needs are completed. These were identified from the Organization (department) nDSM (Figure 6) and are defined at home location $k = 1$ efficiency levels. While we have assumed that these are constant (as mentioned by NHEDD), they can be extended for a growing organization by using w_{jt}, $c_{jj't}$, and c_{jdt}.

Architecture constraints (10) and (11) introduce the organization architecture. As discussed in section 2, any product development task comprises work and coordination time. For any work to be performed, a proportionate amount of coordination 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 the organization (department) nDSM (Figure 6). Equations (10) and (11) ensure that this ratio (at home location $k = 1$ levels) is maintained with every workload allocation. 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 optimization exercise could have allocated the work time and coordination time to different locations. The RHS of the constraint is obtained from the Organization (department) nDSM (Figure 6). It reflects the organization architecture and is constant.

The capacity constraints (12) ensure that the manpower changes at any location, between time periods, is constrained. $x \leq 1$ with $\leq$ inequality implying that downsizing between successive periods for location k is constrained. Such constraints are often motivated by strategic and political considerations. Similarly with $\geq$ inequality and $x \geq 1$, the increase between successive periods is constrained. This constraint was used for the GPD location $k = 6$, as NHEDD wanted to ensure that the learning rate (and hence efficiency improvements) was maintained. It can also be used for locations (GPD or otherwise) that are constrained in availability of appropriate manpower.

3.3.2. Analysis of the Formulation. The non-linearities in the objective function were linearized as

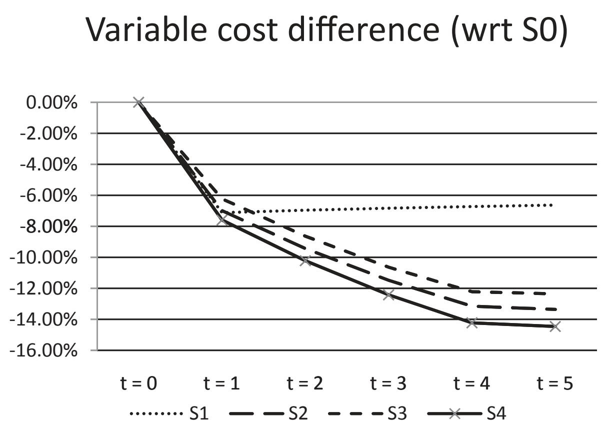
$$\min \max(x, 0) \quad \textit{is linearized as} \quad \min g \quad \textit{subject to } g \geq x, \quad g \geq 0.$$

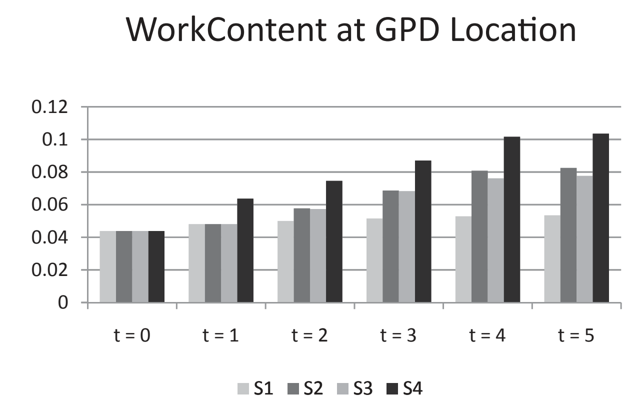
The constraint set consists of linear equations, thus forming a convex set. The simultaneous presence of a convex constraint set and a linear objective function ensures that the above formulation is a linear programming problem. This gives two very important implications (Bertsimas and Tsitsiklis 1997): the problem is now solvable in polynomial time and there exists a corner point (unique) solution with no duality gap. Thus, we can develop such problems for a very large number of departments or we can solve such problems at the task level rather than at the department level (with appropriate constraints). In a general case, many firms may use a manpower head count in lieu of manpower task time. Then we would have a mixed integer program and hence, no closed form solution in most cases. In NHEDD's case, the manpower allocated to each department/location is high and, hence, there was no need to use integer restrictions (agreed with the division).

Figure 9 Optimization Results

Total Cost Reductions

Case	S1	S2	S3	S4
wrt S0	5.89%	7.77%	7.01%	8.55%





3.4. Results

There is an existing manpower distribution for NHEDD (Figure 7). We find the objective function value with this arrangement (incorporating the learning rate at the GPD location) and treat this as the base case *S0*. We solved the formulation for various cases and compared the results with *S0*. We present four of the cases here:

- *S1*: Single redistribution decision. Any reorganization only takes place between $t = 0$ and $t = 1$.
- *S2*: Multi-period redistribution decision. Reorganization can take place in any time period, and each department retains current location assignments.
- *S3*: *S2* with "competence preserving," that is the work allocation for a (*jk*, i.e., department-location) combination will not go below $y\%$ of that at $t = 0$ for that combination. ($w_{jkt} \geq y{*}w_{jk(t=0)}$). A motive for this is to ensure that the relative efficiencies do not suffer if the work allocation reduces in one time period and then increases in a subsequent time period.
- *S4*: Multi-period redistribution with "GPD expansion." *Case S2* above but with the flexibility for all departments to expand to the GPD location $k = 6$.

We solved the optimization problems corresponding to the various cases using CPLEX software. The optimization results are outlined in Figure 9. The difference in cost reductions (with respect to *S0*) realized between case *S1* and cases *S2*, *S3*, and *S4* shows that most restructuring happened in the first time-period. The cost reductions increased with flexibility. These cost reductions (savings) translated to significant gains in absolute numbers for NHEDD.

There are two important considerations in these results: (a) the slope of the variable cost difference (Figure 9) of the various cases increases with *t* because most restructuring happens in the earlier time periods (recovery of fixed costs associated with restructuring): this is a function of NHEDD's planning policy and will differ by firm. (b) The total content that is performed at the GPD location rises from 4% to approximately 8% in *S2* and *S3*: such limited expansion at the low cost location is driven by the capacity constraints used (Equation (12), Figure 10). These results will vary by the strategic directions followed by respective firms and the related constraints defined by such directions, for example, the related capacity constraints, budget constraints if any (not used in this example), changes in the time horizon used, etc.

3.4.1. Robustness.

The robustness of the methodology had to be reviewed with respect to the modeling effort and the data used. In our case, robustness of the mathematical model is established (as we could transform it to a linear program), but robustness of the data development process has to be considered

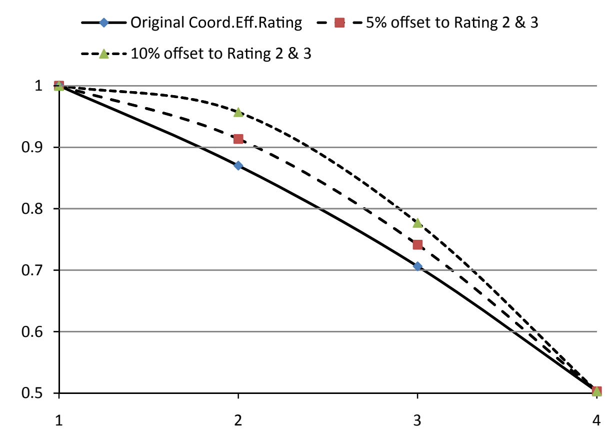
Figure 10 Robustness of Methodology (Impact of Qualitative Data)

		S0	S1	S2	S3	S4
			Results with respect to S0			
Base Case Results			5.89%	7.77%	7.01%	8.55%
Coordination Time in Org. Arch. (*Fig 6*)	-10%	-0.60%	5.74%	7.66%	6.86%	8.38%
	10%	0.60%	5.18%	7.11%	6.35%	10.02%
Coordination Efficiency (offset to ratings 2 & 3)	5%	-0.65%	4.60%	7.68%	6.84%	
	10%	-1.25%	3.41%	7.60%	6.69%	

Figure 11 Coordination Efficiency Changes

Relative Efficiency Ratings at t=0

$\theta_{kk'}$	k=1	k=2	k=3	k=4	k=5	k=6
k=1	1	2	2	3	3	4
k=2	2	1	2	3	3	4
k=3	2	2	1	3	3	4
k=4	3	3	3	1	3	4
k=5	3	3	3	3	1	4
k=6	4	4	4	4	4	3



(though we did a validation check of actual manpower allocation; Figure 7), particularly when qualitative inputs have been converted to quantitative data (potential for misinterpretation of data). We had two such instances.

Work Time and Coordination Time. This separation was identified by representatives of various departments based on their experiences over various development programs. This data is first identified in Figure 5 and then mapped to the organization nDSM (Figure 6). Since the total time is fixed (based on manpower allocation per NHEDD program allocation rules), any change in work time is accompanied with changes in the coordination time. The impact for ±10% changes in the coordination times in the organization nDSM (Figure 6) is shown in Figure 10. This has <1% impact on the base case *S0* and savings of the other cases (with respect to their respective *S0*) were on similar lines as the basic formulation results. The results show that the short term impact (*S1*) of misinterpretations in this data is limited, but the impact increases (positively) with more flexibility (*S4*).

Coordination Efficiency. We had used a rating scale of 1–4 to classify the coordination efficiency between various locations (section 3.2 and shown in Figure 11) and had transformed this to obtain coordination efficiency factors ($\theta_{kk'(t=0)}$). The values for ratings 1 and 4 were known, and there were qualitative assumptions available for ratings 2 and 3. We present the results for 5% and 10% offsets in efficiency factors corresponding to ratings 2 and 3 (Figure 10). While the savings for cases *S2* and *S3* were similar to those in the base model, those of *S1* were marginally off. This showed that misinterpretations in coordination efficiency data had limited long-term impact on the results but (relatively) significant short-term impact as the coordination challenges with the GPD location were overriding the manpower rate benefits and the immediate learning by doing effects.

3.4.2. Sensitivity Analysis. GPD is impacted, dynamically, by changes in the economic, social and political environments. These changes impact the capacity constraints used and the exogenous variables that influence the various GPD decisions. Figure 12 shows the results of our sensitivity analysis study.

Figure 12 Sensitivity Analysis of Capacity Constraints and Variables

Constraint / Variable	change to/by	change from optimal case in Fig 9 (w.r.t. case S0: no change in work distribution)			
		S1	S2	S3	S4
Capacity constraint at loc k = 1 (home), unconstrained earlier	0%	0.00%	-0.72%	-0.76%	-0.62%
	1%	0.00%	-0.56%	-0.60%	-0.47%
	3%	0.00%	-0.28%	-0.29%	-0.21%
Capacity change at loc k = 2,3,4,5	-1%	-0.21%	-0.37%	-0.33%	-0.36%
	1%	0.21%	0.35%	0.30%	0.36%
	10%	1.86%	2.96%	2.08%	3.04%
Capacity change at loc k = 6 (GPD)	-5%	0.00%	-0.01%	-0.01%	-0.11%
	-1%	0.00%	0.00%	0.00%	-0.02%
Learning rate at loc k = 6	-10%	-0.02%	-0.06%	-0.06%	-0.03%
	-5%	-0.01%	-0.03%	-0.03%	-0.02%
	5%	0.00%	0.03%	0.04%	0.02%
	10%	0.02%	0.06%	0.07%	0.05%
Manpower rate at loc k = 6 (GPD) (change every year))	1%	-0.09%	-0.12%	-0.12%	-0.15%
	5%	-0.35%	-0.49%	-0.49%	-0.91%
	10%	-0.51%	-0.82%	-0.75%	-1.31%

-ve % change implies that the cost increases from the optimal case in *Fig 9*

S1: single redistribution decision between t =0 and t =1
S2: multi-period redistribution (re-organization can take place in any period)
S3: S2 case with `competence preserving'
S4: S2 but with all departments being allowed to expand to the GPD location k =6

Capacity Constraint Changes. Our results for NHEDD were impacted by the capacity constraints used. Review of the results showed that these constraints were active for various locations at different time periods (Figure 13).

The results in Figure 9 had been obtained with no capacity constraint at the home location $k = 1$. In our sensitivity analysis we introduced constraints for this location, as it is challenging to find appropriate manpower at the NHEDD's home location at Finland. On constraining the year-on-year work allocation increase to 0%, 1%, and 3% at $k = 1$, we observed that the total costs increased. Thus this is an issue that NHEDD needs to focus on. Similarly we considered changes in this capacity constraint by -1% (less flexible), 1%, and 10% for locations $k = 2,3,4,5$, as NHEDD did not see major efficiency improvements taking place in these locations. The results show that flexibility in year-to-year work content increases at these locations provide an opportunity for further cost benefits. At the GPD location $k = 6$, NHEDD prioritized efficiency improvement with learning effects. So, we considered changes of -1% and -5%, that is, if efficiencies are not realized, the work content offshored to the GPD location will not be increased as planned. Here we observed that with these enhanced constraints, costs increased, though not to the magnitude seen when introducing capacity constraints at the home location $k = 1$ (possibly due to the lower work content performed at $k = 6$; see Figure 9). The sensitivity analysis show that NHEDD needs to evaluate manpower availability at the home location and look for opportunities to perhaps supplement shortages through transfers from other locations to further cost benefits.

Variables at GPD Location $k = 6$. Besides the ability to recruit appropriate manpower at the GPD

Figure 13 Active Capacity Constraints

Case S1

Loc\time	t = 1	t = 2	t = 3	t = 4	t = 5
k = 1					
k = 2	y				
k = 3	y				
k = 4	y				
k = 5	y				
k = 6					

Case S2

Loc\time	t = 1	t = 2	t = 3	t = 4	t = 5
k = 1					
k = 2	y	y			
k = 3	y	y	y	y	
k = 4	y	y	y	y	
k = 5	y	y	y		
k = 6		y	y	y	

Case S3

Loc\time	t = 1	t = 2	t = 3	t = 4	t = 5
k = 1					
k = 2	y	y			
k = 3	y	y	y	y	
k = 4	y	y	y	y	
k = 5	y	y	y		
k = 6		y	y		

Case S4

Loc\time	t = 1	t = 2	t = 3	t = 4	t = 5
k = 1					
k = 2	y	y			
k = 3	y	y	y	y	
k = 4	y	y	y	y	
k = 5	y	y	y		
k = 6	y	y	y	y	

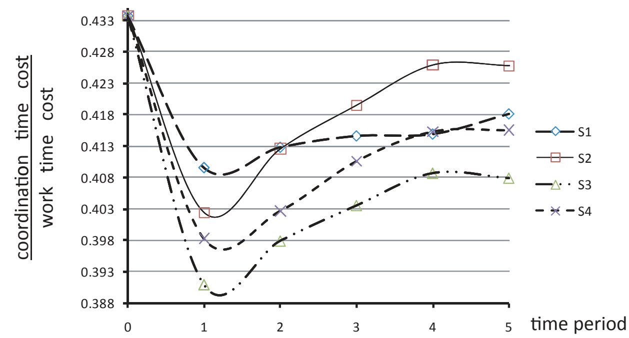
location, NHEDD was also likely to face the challenge of maintaining the learning rates and be affected by fluctuating, usually adverse, manpower rates (due to a combination of labor availability and exchange rate changes). The changes in the learning rate are critical to NHEDD's need to achieve relative efficiency differences. We analyzed different scenarios with respect to these possibilities and they are shown in Figure 12. As seen from the results, NHEDD will be significantly impacted by adverse movements of the manpower rates. This provides support for constraints like Equation (12), where NHEDD can ensure that in addition to offshoring, certain competencies are retained at existing locations to help tide over issues like manpower rate increases at a GPD location.

We have presented certain sensitivity analyses here. Our modeling approach in section 4 is general enough to perform a sensitivity analysis of any range of constraint and variable changes, either individually or in various combinations. From Figure 13 we observe that the results are most sensitive to availability of appropriate manpower at the home location $k = 1$ and the manpower rate changes at $k = 6$, and the best opportunities lie with the ability to reduce manpower allocation at locations $k = 2,3,4,5$ more than that outlined in the capacity constraints. We recommended that NHEDD work on the strategic considerations (manpower allocation) of locations $k = 2,3,4,5$, and review the model on an annual basis, primarily updating the manpower rate information and the observed learning rate at $k = 6$.

3.4.3. Observations. In the course of our development of the model in section 2, we had identified the separation of task time into work time and coordination time. Thereafter, we defined the index of modularity (2), and, subsequently, we identified the index for each department (Figure 6) and ranked the departments based on this index (Modularity Rank [ModRk] in Figure 6).

Given our objective function and the challenges in coordination between locations (relative coordination efficiency), we would expect that optimization would drive toward reducing the costs attributable to coordination time with respect to the costs attributable to work time. So, for each case (Figure 9), we segregated the variable cost at each time period into coordination time cost and work time cost and observed this ratio (Figure 14). This ratio, for each case, reduces significantly during the first time period ($t = 1$) but increases thereafter. NHEDD had expanded to the offshore location based on "it felt to be the right thing to do." The departments that had operations at GPD location $k = 6$ had modularity ranks 4, 8, 9, and 10 (Figure 6). Similarly the distribution at other locations had not evaluated the coordination needs. So the model results first sought to reduce the coordination needs ($t = 1$). Thereafter, the relative manpower rates and efficiency factors work to accommodate higher coordination for best cost efficiencies.

Figure 14 Analysis of Cost Change from Time $t = 0$



At $t = 0$, the departments with respective ModRk 4, 8, 9, 10 had work allocated at the GPD location $k = 6$. As a further study, we observed the changes in their respective work allocations over time for cases *S2*, *S3*, and *S4* (Figure 15) at $k = 6$. While departments with ModRk 4, 8, and 10 showed increase in work allocation (at times after a minor decrease), a department with ModRk 9 constantly showed a decrease in work allocation (non-monotonic behavior with respect to ModRk). On reviewing the data, we observed that though department with ModRk 9's coordination needs were similar to the departments ranked 8 and 10, its work time efficiency was far higher at the home location $k = 1$ than any other location. So this department's work allocation tends to concentrate at the home location. Thus, in this case, the relative efficiencies, rather than modularity or manpower rate differences, had an impact on the offshoring allocation.

4. Discussion

Our agreement with NHEDD did not provide us with participation or visibility to either the final model selected for implementation or its implementation (the results shared in Figure 9 are some of the scenarios considered). In this section, we discuss the various challenges that may be faced while developing and implementing the model proposed by us. These challenges have been identified based on the various discussions that we have had during our project with NHEDD and various other firms involved in global product development.

4.1. Developing the Model

The first challenge concerns developing the model. As shown in Figure 16, the model requires inputs from different hierarchical levels. Work distribution takes place at the operational or organizational level.

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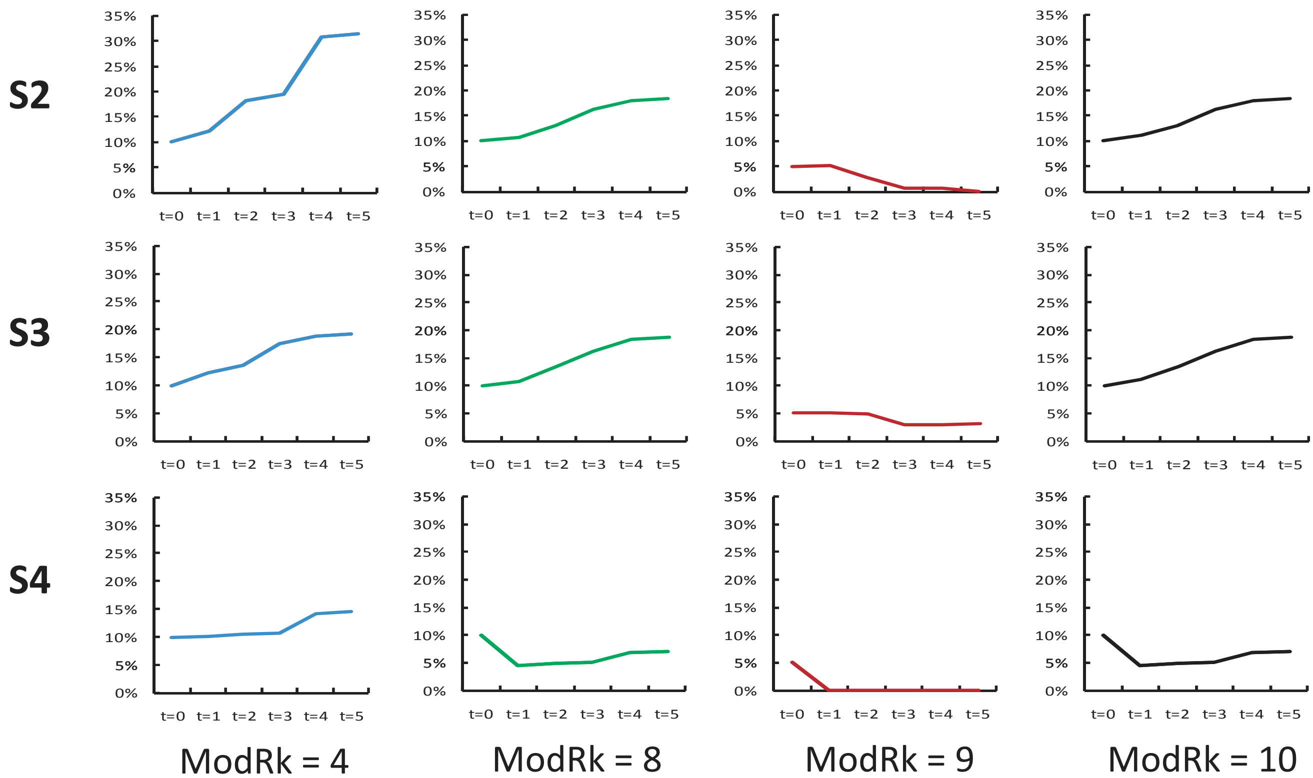
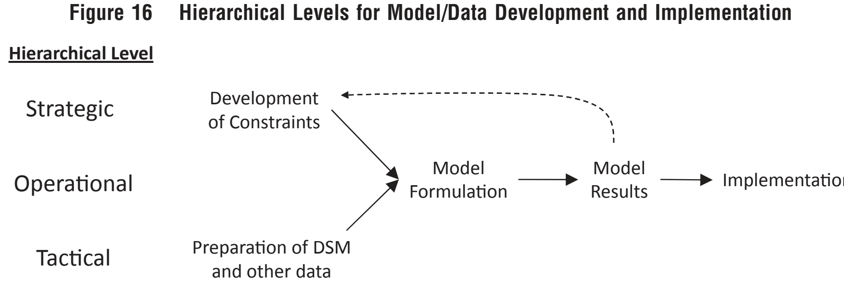
Figure 15 Non-Monotonic Expansion of Departments at GPD Location



However the constraints are defined at a strategic level, for example, how fast should the firm grow (year-to-year) at the low cost development (GPD) center? It is not easy for a firm to define them before initiating such a modeling exercise. Invariably, most firms will start such an exercise without constraints and then, on observing the results, would want to include such constraints. This necessity, often influenced by the model results, is related to the risk perception toward growth of the low-cost development center, implications (personnel issues, political ramifications) of slowing/closing down existing development centers, concerns on change management, etc. Firms go through a "constraint development" exercise, examining the "non-model" implications of the modeling results before they decide on the constraints to be used (Figure 16).

Similarly, the data required for the model are developed at the tactical level, as development work takes place at that level. Data input for DSM development such as information dependencies between tasks (Figure 4), task time split between work time and coordination time (Figure 5), etc. reside at that level. Some of the other data (such as hiring manpower costs, cost of decreasing manpower, etc.) may exist at the operational level though. In general, DSM development is a very difficult task. Most DSM development has been qualitative and use of DSMs in decision theoretic applications (numerical DSMs) negligible. As mentioned in section 3, we had to undertake a number of iterations to develop the numerical DSM. Most development engineers "know" their tasks/responsibilities but find it difficult to document the same. Hence the DSM exercise

Figure 16 Hierarchical Levels for Model/Data Development and Implementation



should ideally be conducted by "system engineering" people who, while knowledgeable about the development process, are not directly involved in development. They should spend significant time in discussions with the development engineers. There should be validations steps (such as the one done at NHEDD for the data of Figure 7) to ensure that data developed is accurate. Sequential steps, such as those outlined by us, of individual interviews, followed by dyadic and triadic interviews, and finally full group interviews help in developing the right DSM.

4.2. Implementation

Redistribution of product development work has its own challenges. Here we discuss some of the key challenges faced therein and the related caution that firms need to adopt. Many of these challenges are strongly interlinked and often occur together, leading to concerns on offshoring development tasks.

4.2.1. Offshoring Content. NHEDD had already offshored certain development work before the initiation of the project. Review of the organization nDSM (Figure 6) showed that these were not the most "modular" departments. Thus, considerations other than coordination needed with other departments were responsible for the selection of these departments during initial offshoring. In such cases, further expansion of development activities is influenced by the content already offshored. At times, the mathematical program may propose moving back the content already offshored and prefer moving other development content offshore instead (dependent on the organization nDSM). As our case example shows, relative efficiencies also play a significant role in identifying the offshoring content. Firms need to identify mechanisms to initially estimate and subsequently measure the relative efficiency and learning rate parameters for various development tasks at a GPD center.

4.2.2. Awareness. Often, specially in large development organizations, firms offshore certain development work, and this action (and its contents) is not communicated across the organization. This results in departments who have coordination needs with departments whose tasks are offshored finding it difficult to identify their coordinating partners, leading to program delays. Organizations practicing GPD should ensure that the distribution (location) and responsibility of each development task is defined as part of the system development phase (e.g., range planning in case of NHEDD) deliverables for each program.

4.2.3. Resource Availability and Capacity Changes. Firms will face resource availability challenges as they expand their offshore development centers in two ways: (a) availability of suitable development engineers, and (b) an internal challenge of identifying and assigning the right (experienced) development engineers to train the local GPD engineers (in NHEDD's case, this is reflected in the variables SU_k and SUD_{jk}). Firms need to incorporate these factors judiciously. Similar issues can arise at other (than low cost offshore) locations. Reducing the development capacity in such locations may lead to human resources issues, political implications, etc. While the foreseeable issues could be incorporated during constraint development, unforeseeable issues (that occur *ex post*) could require rolling back the development capacities to earlier levels.

4.2.4. Achieving Efficiencies. Our modeling efforts have considered the relative efficiencies in development work between different development centers (locations) dynamically by utilizing learning rates. However, achieving higher efficiencies successively at the GPD location is affected by the availability of appropriate resources (discussed earlier), increase in development capacity allotted, the absorptive capacity of the GPD development center (leading to learning rates), and the cultural challenges at the GPD location. NHEDD used existing data to determine the learning rate and used the learning rate to predict future relative efficiencies (the learning rate was maintained through controlled expansion at the offshore location).

The discussions in the preceding two subsections highlight the various types of challenges, and associated uncertainties, associated with developing and implementing a mathematical modeling approach to work distribution in a product development organization. As identified in most of the above cases, constraint development though key is constrained by the inability to foresee the challenges. In NHEDD's case, the robustness study (subsection 3.4.1) and the sensitivity analysis (subsection 3.4.2) establish that the model was suitable for implementation. However, this was a function of the data and constraints used, and may not hold for other firms. Given the learning rates in product development and the "innovative" nature of the work, it is very important for firms to be patient with the results of GPD (primarily measured through relative efficiency resulting in corresponding work time and coordination time). Hence, they should estimate learning rates/relative efficiency factors and develop constraints accordingly while adopting and implementing such mathematical models.

5. Conclusion

Our results (cost savings) presented significant opportunities for NHEDD to restructure their existing work allocations. The current assignments to the GPD location required significant coordination and hence challenged PDD effectiveness. While strategic needs may constrain NHEDD from allocating work away from some of the established development centers globally, they also face constraints in increasing work assignment at their home location. Hence, they need to expand at the GPD center to meet increasing work needs, which has its own share of uncertainties. They need to carefully re-evaluate the tasks that have been offshored to the GPD center. As shown by the sensitivity analysis, this approach is the only way to protect against manpower rate increase (relative) at the GPD location and uncertainty in the learning rate of the GPD location.

The contributions of this study are many-fold. Our choice (arguing through precedent literature) of the trade-off criteria, incorporation of the same in a mathematical model, development of data using DSMs (developing nDSMs), introduction of architecture constraints (Equations (10) and (11)), etc. provide a suitable example that firms can follow toward the design of their product development organizations. At the same time, the model developed by us is very general and can be easily modified to incorporate suitable nuances of respective firms, for example, addition of new locations, different fixed cost structures (investment in land, building, etc.), and so forth.

On the research front, while earlier studies have highlighted the challenges toward offshoring in complex engineered systems (section 1 has a brief review of these studies), they have paused while stating that firms engaged in the design and development of such systems should either identify modules for offshoring or improve means of coordination. Our proposal to allocate and distribute PD work by identifying and separating the work time and the coordination time (using DSMs to quantify them, respectively) is an important contribution in this field of research. To our knowledge, this is the first use of linked DSM-Mathematical Programming for the design of product development organizations, especially those distributed over multiple global locations. Similarly, our result that shows a non-monotonic increase of offshoring content with respect to the modularity index challenges the existing notion of offshoring modular content and invites further research into trade-offs that may exist in offshoring decisions, for example learning rate, absorptive capacity, etc.

Parker and Anderson (in press) have identified various themes along which this research has progressed. Our research would form part of the "organization network design" theme. As they state, a vast majority of the literature in that theme "is at the organizational level of analysis, or too abstract from an operational point of view to be used to design distributed project organizations." Our study addresses this gap and provides a base model and methodology for future researchers to build on.

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