Organizing Global Product Development for Complex Engineered Systems

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***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 paper, we explore such 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 distributions, the product and process structures, and their interplay with 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. Based on these implications, we propose a process for firms to follow as they pursue GPD, while recognizing that: first, modularity in design and development and modularity in manufacturing need not be the same, specially in complex engineered systems (CESs); and second, system architecture development is a core competence of the firm designing and developing CESs, and this activity should be retained at the home location. We conclude with potential research directions on the subject of global PD.**

***Index Terms*—Global issues in technology management, global organizations, new product development (PD) process, organization design, R&D management.**

I. Introduction

THE SUBJECT of global product development (GPD) is generating a lot of interest. GPD has been defined [1] as combining certain centralized functions with some engineering and related product development (PD) functions that are 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, distributed PD (DPD) is defined [2] as the use of organizational arrangements involving multiple organizations that are separated by firm, geographical, or other boundaries, that are used for PD. From these definitions, we infer that GPD is an organization arrangement, which identifies the location and ownership of the PD activities. Thus, the GPD activity, besides involving offshoring, can be performed either through captive engineering/development centers, outsourcing (see Fig. 1) [1], [3], or hybrid forms.

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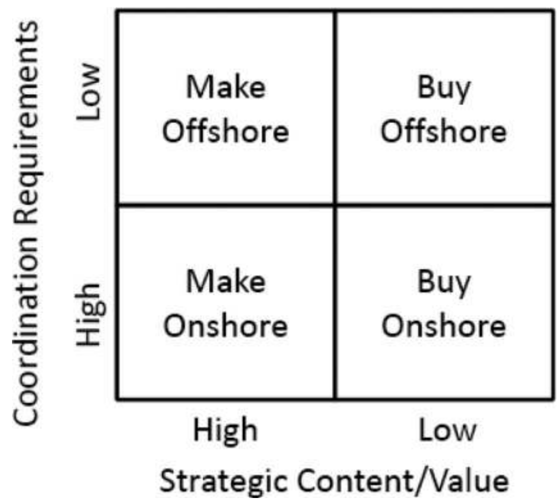

Fig. 1. Sourcing-location matrix.

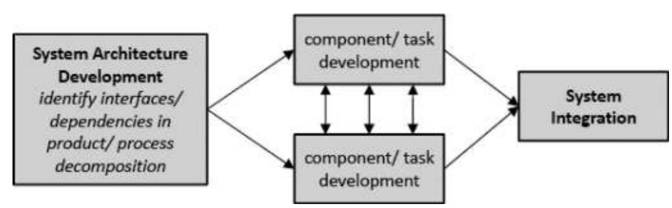

Fig. 2. PD process for complex systems.

Firms pursue GPD either to meet global market needs (locations other than home location) or to seek efficiencies [4]. The drive toward 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 [1]. However, developing products across geographical boundaries present associated challenges in coordination, communication, differences in culture, different time zones, etc. [2], [5], [6]. This requires a careful selection of the PD tasks that are to be offshored.

The selection of such PD tasks is further complicated in the case of complex engineered systems (CES). CES comprises a number of components and processes with interdependencies during development. Development of CES involves decomposition followed by integration of the system. Typically, this would comprise system architecture development, followed by component development, and finally system integration (see Fig. 2) [7]. During system architecture development, the constituents of the system and their respective interdependencies are planned, and their respective performance requirements specified.

	Research / Turnkey Development		Global Product Development	
	Govt. controls, closed markets, limited IT bandwidth	Open markets, collaborative tools, increased IT bandwidth	simultaneous development of products by teams distributed globally	
	upto mid 90s	*from mid 90s*	*2000s*	
			'simple' systems	***CES***
Why do firms do global R&D or product development?	Julian & Keller (1991) [10]	Kummerle (1997) [4] Roberts (2001) [11]	Eppinger & Chitkara (2006) [1] Khurana (2007) [3]	
How do firms organize for distibuted R&D or product development?	Hakonson & Zander (1988) [12] Howells (1990) [14] Julian & Keller (1991) [10] Ogbuehi & Bellar Jr. (1992) [15] Graber (1996) [13]	Kahn & McDonough III (1996, 1997) [44], [45] Moenaert & Caeldries (1996) [16] Chiesa (1996, 2000) [18], [19] von Zedtwitz & Gassmann (2002) [17]	Subramaniam, et. al. (1998) [20] Eppinger & Chikara (2006) [1] Khurana (2007) [3] Anderson, et. al. (2008) [2] Gomes & Joglekar (2008) [21]	Gap Explored in this Research

Fig. 3. Research in GPD.

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.

Our review of existing academic literature revealed that while the literature on offshoring of PD activities is wide, there exists a gap in understanding how GPD for CES should to be undertaken, i.e., what is the organization form (ownership) that the firm should pursue? How should the firm determine the content (decomposition method) to be offshored? How do they relate to the firm's GPD intent? What process should a firm follow in its GPD efforts?

We address such questions in this paper. Since GPD for CES is a nascent topic, we follow an exploratory case approach [8], [9]. We analyze the GPD efforts of five firms engaged in the design and development of CES. We explore the relationships between their GPD motives, the PD content that had been offshored for development, and system architecture. We also outline other experiences and learnings that these firms had as a part of their GPD organizations. We draw on our observations from these case studies to arrive at organizational and architecture implications for CES developing firms that are pursuing GPD. We then build on these observations to propose a GPD process that a firm may follow.

Our paper progresses thus: in Section II, we provide a brief survey of related literature on offshore PD, identify the literature gap, and develop the research question. In Section III, we justify and describe the case methods adopted by us to address the research question. We describe our case studies in detail in Section IV. We summarize our case study observations in Section V, and then build a suggestive model [8] that firms adopting GPD can follow in Section VI. We conclude with some thoughts on GPD and directions for future research in Section VII.

II. Research Focus

A. *Literature Review of Offshore PD*

Our research interest in the area of GPD relates to the special case of DPD when the PD locations are significantly separated in terms of time zones, geography, culture, etc. There is substantial literature on such global R&D activities. Early literature in this field focused on research or turnkey development, and was influenced by the prevailing economic environments and available information technology (IT) capabilities. Collaborative PD (GPD), whereby different processes or components of the product are simultaneously developed in dispersed parts of the world, has gained increasing attention since the 2000s as a research topic.

Offshoring of turnkey development is very difficult for CES. Rather, offshoring of PD activities would proceed in steps, possibly starting with the development of a part/component and growing to subsystem development [1]. Thus, organization of GPD, i.e., how are activities distributed over respective locations, or how do firms do GPD, is critical for CES. The organization of GPD activities is dependent on why the firm is pursuing GPD, amongst other reasons. We outline key papers in existing literature on why firms pursue GPD and how they organize for GPD in Fig. 3.

The reasons for firms to expand their R&D activities globally have grown over the years. Julian and Keller [10] identified a variety of reasons for firms to pursue distributed R&D: political motives; government incentives; closeness to markets; access to technology; etc. Kuemmerle [4] summarized the reasons well by stating that firms establish R&D capabilities abroad to either augment or to exploit their home-base capabilities. Firms establishing R&D capabilities abroad to augment their home-base capabilities do so to absorb knowledge from the local scientific community, create new knowledge, and transfer it back to the firm's central R&D site (these views were echoed by Roberts [11]). Other firms look at exploiting the knowledge base at the home base by transferring and commercializing it. Eppinger and Chitkara [1] and Khurana [3] added to these definitions by stating that firms practice GPD for cost reasons too, taking advantage of labor arbitrage. This has become a key reason for firms to pursue GPD (solely pursuing development work but not research activities) and is an outcome of significant advances in digital engineering tools and IT bandwidth.

Early literature recognized the challenges faced with government controls and limited IT bandwidth. Prescriptions on how to practice globally distributed R&D included corporate R&D

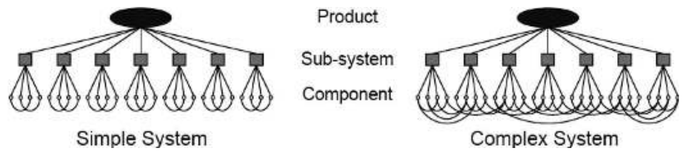

Fig. 4. Simple and CESs.

to coordinate and regional R&D to manage details of respective R&D responsibilities [12], [13], keep research central and spread development next to manufacturing [14], look for joint ventures or acquisitions [10], and provide more flexibility to distributed R&D centers [15]. With improvements in IT bandwidth, the opportunity to develop a network of R&D facilities was recognized (though Moenaert and Caeldries [16] continued to be concerned with the challenges of large distances between development centers). von Zedtwitz and Gassmann [17] defined four archetypes of R&D internationalization: national treasure (both research and development are done domestically)' technology-driven (development is domestic and research dispersed); market-driven (research is domestic and development dispersed); and global R&D (both research and development are dispersed). Chiesa [18], [19] differentiated foreign R&D facilities between specialization-based (global responsibility for a product/process/technology) and integration-based (contribute to technology development and are networked). Researchers during this period did recognize the social and cultural challenges of such distributed R&D facilities and advised improvements in communication methods including face-to-face meetings, cross-location teams, etc.

Since the early 2000s, as more firms started practicing GPD, Subramaniam *et al.*. [20] recommended cross-national teams, particularly when processing tacit knowledge. Recent literature, while accepting the adoption of GPD by firms, is concerned on the coordination challenges across locations [2], [21]. They have recommended offshoring development of modular tasks or architectural changes to introduce modularity. However, they have not discussed the implications of the architecture changes. Eppinger and Chitkara [1] have proposed a three-staged approach to GPD starting with process outsourcing of simple and then integrated tasks, followed by component outsourcing (simple, then integrated, and finally modules), and finally establishing captive design centers (in a staged manner from simple tasks or components to new global products). Khurana [3] has proposed a staged development for the offshore R&D center, moving from a tactical role to a more strategic role. Eppinger and Chitkara [1] have alluded, in a limited way, to the organizational form of GPD (see Fig. 22), but do not relate it with GPD intent.

Though literature has discussed why firms pursue GPD, or how they pursue GPD, it does not connect the two, i.e., how a firm's GPD intent influences how it pursues GPD. This is one of the gaps that we address in this paper.

B. Complex Engineered Systems

CESs (see Fig. 4) are networks of components that share technical interfaces to function as a whole [22]. They have behaviors and properties that no subset of their elements have [23]. CES generally comprises a large number of components. In such cases, a hierarchy can be established wherein the product or system is decomposed into subsystems, and those subsystems are further decomposed into components. There could be more than a single level of subsystem 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 [24]. The subsystems within the system and the components within a subsystem are interconnected or dependent on each other and these relationships define the system architecture.

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 [24] 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 observed as product architecture, process architecture, organizational architecture, etc. Ulrich [25] 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. Process architecture is the set of tasks and the related information flow between them that sum to produce the final product/system. Organizational architecture organizes the subteams in a project involving the development of a system/product and the relationships, in terms of information flow, hierarchy, etc., existing between these subteams. Studies [26] 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 firm [27].

CES are difficult to study, design, or source as an entire system. Hence, they need to be decomposed [28] into sub-systems or modules such that each module becomes a black box, hiding design details from other modules. Such decomposition is necessary to identify the cause of a problem, to identify a level of module/component that can be designed or outsourced, or a level at which a sub-team may be assigned responsibility. The modules may be further decomposed to tasks or components (Fig. 5). At the component/task level, there could be a need for significant coordination during product development. This becomes challenging when such a component/task is offshored and it needs coordination across locations.

Due to these factors, it is rare for a firm engaged in the development of CES to offshore the complete development in a single phase. It may happen though if the product is being supplied by an ODM. At times, the design and development may be

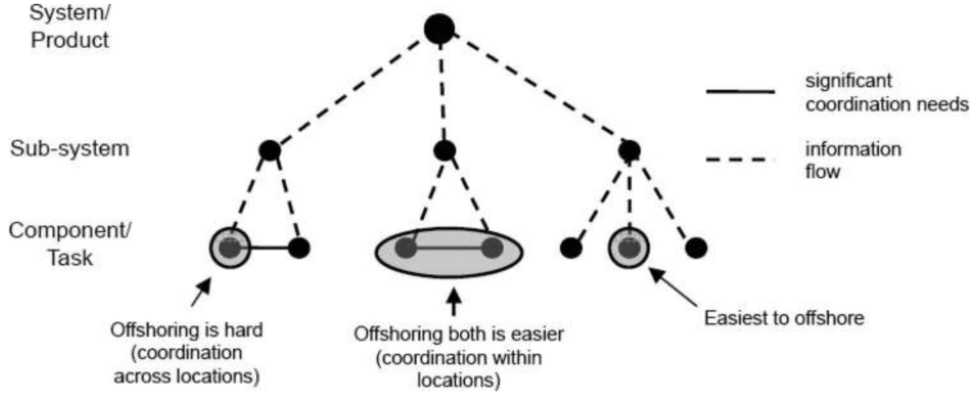

Fig. 5. Offshoring difficulties.

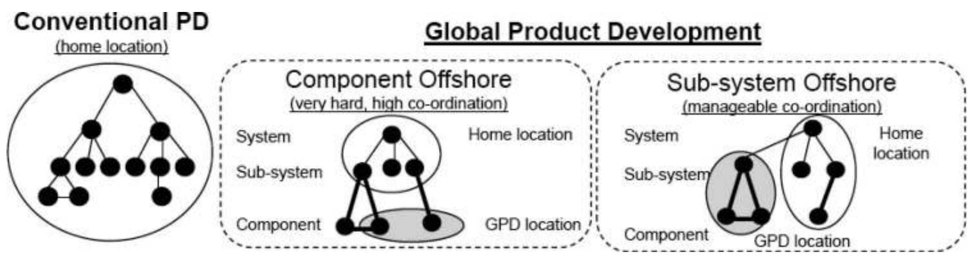

Fig. 6. GPD architecture.

offshored (with outsourcing) to design houses, captive development centers, or engineering services firms, but these become rare as the complexity of the system 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. In a few cases, the firm may offshore a component of the CES despite the coordination needs with other components that are not offshored and an inability to identify the necessary interfaces [29]. Such cases generally happen with outsourcing, where the supplier with the necessary competence happens to be offshore (a happenstance), e.g., Pitney Bowes (PB) (see Section IV) could identify the interface needs to ensure outsourcing to an offshore supplier Canon such that there are limited coordination requirements during component development.

Thus, the different approaches to offshoring for CES are component offshoring and subsystem offshoring (see Fig. 6). Each of these GPD organizational arrangements has its respective benefits and challenges. While subsystem offshoring may ensure that coordination needs are controlled within a location, it could lead to a loss of subsystem development capability at the home location. Similarly, component development offshoring would require significant coordination across locations and a potential loss of efficiency. Identifying the right set of tasks to offshore is an important factor toward successful execution of GPD [29], [30]. This requires decomposition studies to be done.

C. Research Question

Besides the gap in literature identified in Section II-A, there is a void in literature in addressing how firms need to offshore development of CES (shown as gap in Fig. 3). Even recent studies [1], [2], [21], [31] assume that either 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), or possible to introduce modularization. Such assumptions may not hold in the case of CES due to the information dependencies/coordination needs, as discussed earlier. Therefore, an appropriate system architecture analysis, using an appropriate decomposition technique, is needed to understand the product or process, and then identify the suitable content for offshoring.

The questions that reflect the aforementioned gaps (for a firm developing CES) are: How does the GPD intent of the firm influence the organization form (ownership) that the firm should pursue? How should the firm determine the content (decomposition method) to be offshored? How does the decomposition method relate to the firm's GPD intent? How should a firm pursue its GPD efforts?

We explore these questions in this paper. Since the variety of firms that practice GPD is very large, in this paper, we explore these questions for those firms that are engaged in GPD to augment their home-base development efforts, and which do not adopt architecture changes as a part of GPD. The first factor implies that we did not include those firms that pursue GPD to exploit their home-base development capabilities in global markets because, often in such cases, GPD follows offshore manufacturing. The other factor is followed by most firms. Firms rarely do changes in system architecture to pursue GPD. This fact also finds support in academic literature [27], which says that the prevailing architecture shapes the information flows in a firm and changes to the architecture lead to the firm's collapse.

III. Methods

Edmondson and McManus [8] stress on achieving methodological fit in management field research by achieving consistency between the research question, prior work, research design, and contribution to literature. Our research question addresses a gap in academic literature regarding GPD of CES, in particular the absence of any connection between a firm's intent for pursuing GPD, how it structures GPD, and the type of architecture decomposition that it should follow. Given this dearth of related research, case studies represent an appropriate fit [9]. Fisher [9] argues that cases are a wonderful way to begin to formulate research problems and hypothesis because they document the particular issue experienced by a firm. Discussions with such firms enable a deeper understanding of an issue so that subsequent research can be guided by better questions. These case studies (largely based on interviews and observations) could extend to the formulation of hypotheses or principles, which can be tested through econometric data (descriptive) or analytical studies (prescriptive) in subsequent research.

Our research question would be termed as "nascent theory research" [8], i.e., topics that have attracted little research/theorizing till date or represent new phenomenon. Edmondson and McManus [8] state that such research, at best, only proposes tentative answers to novel questions of how and why. Citing papers in nascent theory research, they identify that research in nascent theory is exploratory with qualitative data generated through observations, unstructured and semistructured interviews, archival data, etc. The contribution of such research is a suggestive model to address the research questions and may include the introduction of new constructs. Our constructs, relating to the research questions, were: GPD intent; organizational form; and architecture/decomposition methods.

Since we are exploring nascent theory, it was important to chose firms that pursued GPD in distinct ways [32], [33], [34]. Such theoretical sampling was necessary to illuminate and extend the relationship between the constructs [33]. We needed to choose cases that were polar to each other. We opted to identify firms based on their GPD intent since this is the only construct with existing literature that could extent to GPD of CES, i.e., cost savings or competence enhancing. Further, within each type of GPD intent, we opted for atleast two firms in different industries to see if any observed phenomenon in a firm would be replicated across firms. While PB and Intel were identified as they pursued GPD to augment their competencies, Danaher Motion, Cessna, and Honeywell Aerospace were identified as they pursued GPD for arbitrage (cost savings). These specific firms were identified with the support of PTC, our project sponsor.

We shared an introduction note (prior to the meetings) with the firms, outlining our research interest, and the information that we were interested in: Why did they pursue GPD? How did they start on GPD? Was architecture a consideration in their decision process? What type of decomposition did they follow? How did they rate their experience with GPD? What could they have done differently? Being nascent theory research, we opted for unstructured interviews for responses to the aforementioned questions [8] and semistructured interviews while

Firm	GPD Intent	Data Development
Danaher Motion	Cost savings	8 half-days of interviews
Pitney Bowes	Competence	2 days of interviews
Intel	Competence/ Cost savings	2 days of interviews
Cessna	Cost savings	2 days of interviews
Honeywell Aerospace	Cost savings	3 days of interviews

Followed by iterative discussions towards DSM and case preparations

Fig. 7. Case studies done.

detailing their system architecture, which was done using design structure matrices (DSMs). DSM [35] is a project modeling tool that captures the relationships between project tasks or subsystems/components in a matrix form. DSM can be used in organizing tasks in PD [36]. 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 subsystems, tasks, and subteams. 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.

We had detailed meetings with each firm (see Fig. 7). The types of DSMs developed in each case were based on firm specific needs, and respective GPD approaches followed. We analyzed their task structure, the information flows between different processes, and the relationship between their process-based architecture and GPD content for firms that followed a process-based GPD approach. Similarly, for firms that used product decomposition, we analyzed how the product is decomposed to subsystems and parts, the existing interdependencies between the subsystems/parts so defined, and the relationship between the product architecture and GPD content. In our final case study (Honeywell), we came across a firm that was in the process of setting up a new department and was looking at exploiting the labor cost arbitrage to staff the department. Here, the use of task decomposition to subtasks and identification of coordination requirements between the subtasks played a significant role in identifying the tasks that could be located offshore.

These detailed meetings were followed by a set of iterative exchanges toward the development of the DSMs and the cases. Given the nascent theory nature of our research, we opted for within-case analysis [32], [33], as this process allows rich familiarity with each case and for case-specific nuances to become visible before patterns are generalized across cases. In the next section, we describe these case studies.

IV. GPD Studies

A. *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 used air-bearing-based precision motion (linear and rotary) technology to develop machinery for a wide array of industries like data storage, flat panel display, semiconductor lithography and wafer inspection, metrology, etc.

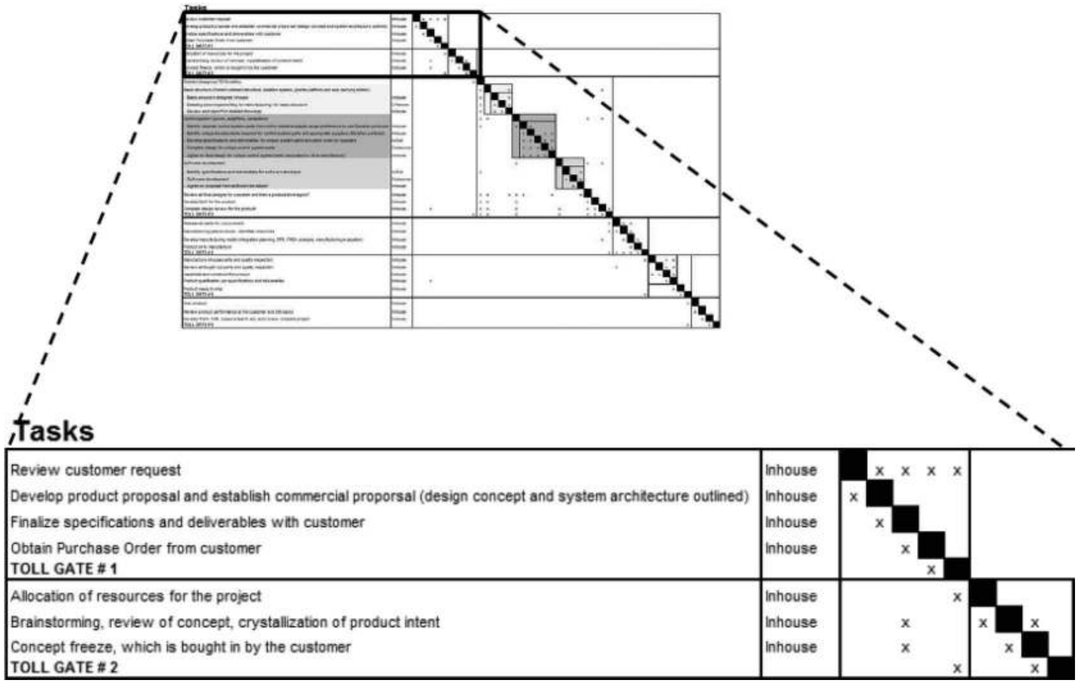

Fig. 8. Danaher Motion process-based DSM.

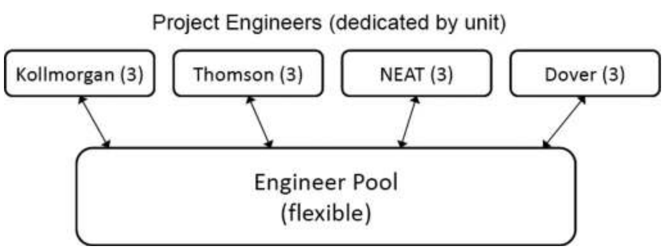

Fig. 9. GDC flexible workforce (*number in brackets indicates number of dedicated project engineers*).

The unit's key competence was its ability to develop customized solutions on a quick order-to-delivery timeline, enabling it to develop a loyal customer base. This quick turnaround required large groups of engineers to work 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. PD at Danaher Motion followed a six-stage-gate process. The duration of each stage gate varied by product and customer need. Decomposition of Dover's PD process is shown in Fig. 8.

Danaher Motion's GPD Efforts: Dover's GPD efforts have evolved through two of three planned GPD phases.

a) *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 a engineering service provider in India. These tasks needed to interact with other tasks (see Fig. 8), most of which were performed in-house 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 their home location.

b) *Phase 2 (Setup of Global Development Center (GDC)):* Danaher Motion then initiated a group intiative, 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 (see Fig. 9). 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.

   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 (see Fig. 8) was the appropriate tool to help identify the same.

c) *Phase 3 (Increasing Utilization to Achieve Efficiency and Scale):* The next phase would require a higher level of involvement by GDC in Danaher Motion's PD efforts. This could involve the transfer of complete component or subsystem design responsibility. From the product-architecture-based DSM (see Fig. 10), 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

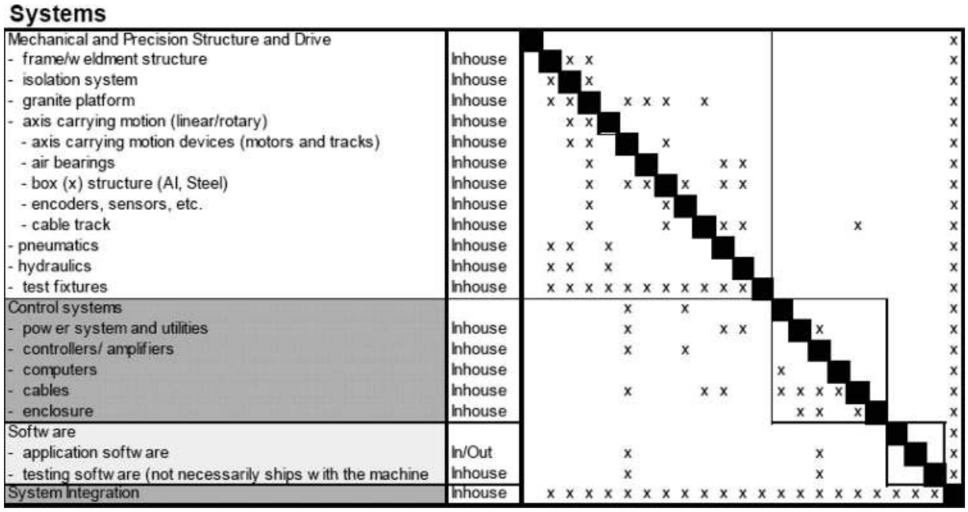

Fig. 10. Danaher Motion product-architecture-based DSM.

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.

Key Insight: 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 be initiated 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, more often, industry norms. There are also immediate cost and productivity benefits from offshoring. It may be difficult, however, to transition to offshoring component/subsystem design as doing so would require training, and the benefits will not be visible until efficiency is gained. Moreover, a quick engineering turnaround company may not want to risk offshoring these responsibilities before confidence in the offshoring center is achieved. The DSM architecture will help to identify appropriate offshoring strategies.

B. PB Mailing Systems: Component Outsourcing

PB is a $5.5 billion firm based at Stamford, CT. Global mailstream solutions is PB's core business. It comprises all the equipment that PB designs, and builds for inserting, sorting, and weighing mail, and affixing postage. PB's design and development centers are at Sheldon, CT, and in the U.K. and France. By the nature of the mail business, product innovation and development at PB is driven by the postal requirements specified in various countries. Only manufacturing related to critical or security-related components of its mailing system is done in-house.

In 2001, PB began developing a new series of mailing systems (MEGA). This was intended to address new requirements of the United States Postal Service, incorporate advances in technology, and provide better customer support and service. This was developed in two series: Fastjet and Midjet, with different output rates. Fig. 11 shows the layout of the Midjet series with its three key modules: user interface (UI); input; and finishing.

PB follows a five-stage Product and Cycle-time Excellence (PACE) PD system [37]. 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 (see Fig. 12).

GPD and 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 in-house, 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. In the architecture-based DSM (see Fig. 12), the firms having responsibility for core design, manufacturing feasibility sign-off, and manufacturing, respectively, for each subsystem/part, have been identified. Cherry, Brother, and Canon are the key companies that support the design, manufacturing feasibility studies, and subsystem/part manufacturing efforts of the MEGA Midjet mailing system.

While the design of the core technology and security components like PSD, MMC, application-specified integrated circuit (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.

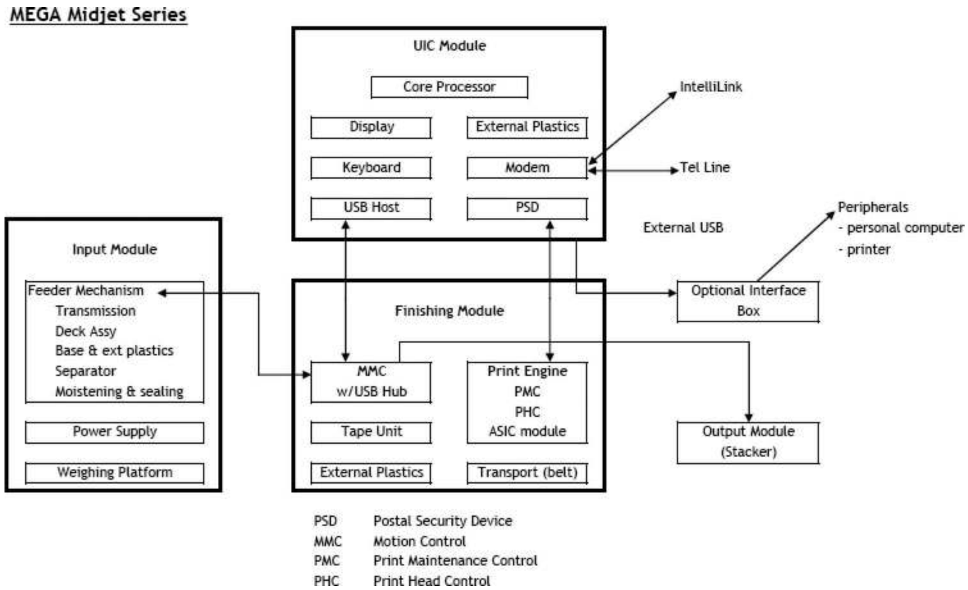

Fig. 11. Schematic of MEGA Midjet Series mail processing module.

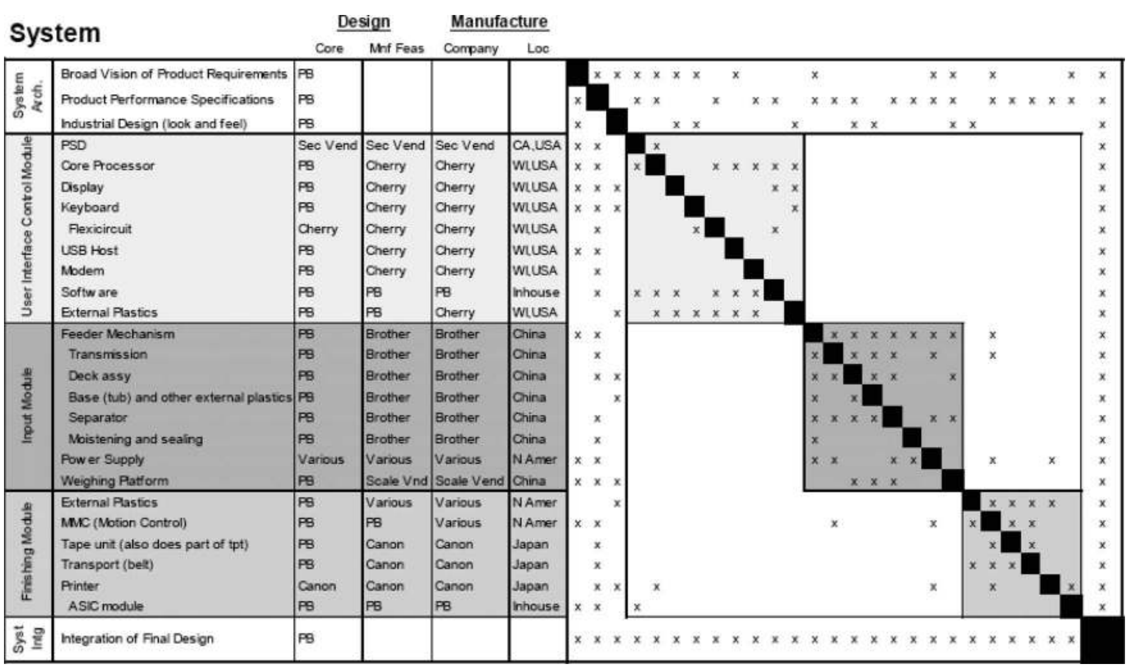

Fig. 12. MEGA Midjet Series architecture-based DSM.

A GPD opportunity involves software development (primarily in the UIC and the MMC), which is becoming a significant portion of MEGA Midjet Series' overall PD. While all software work related to feasibility studies, software architecture, and MMC, PSD, and ASIC softwares 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 noncritical 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 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)

Location of Center	Activity
California	"productization" of design
Oregon	desktop series microprocessors
Colorado	high-end microprocessor design
Massachusetts	high-end microprocessor design
Israel	mobile technology
Moscow	under development
Bangalore	under development

Fig. 13. Intel: specialization by site.

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 Insight: 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 independently developed (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.

C. 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 from several in-house facilities in the United States and Asia/Europe. While the design capabilities among the centers are similar, certain specific *system design* capabilities for various types of microprocessors reside at respective locations (see Fig. 13).

Microprocessor Design and Development: The modern high-end microprocessor is made up of two main parts: multiple cores supported by an uncore, which provides the external interfaces. Microprocessor design and development follows a four-phase process (see Fig. 14): upfront global architecture definition; followed by the design of each unit of the core and the uncore; then complete chip integration; and finally, productization and manufacturing preparation.

Intel had identified the capabilities to develop the core and uncore units as general, which could be performed at any development location. As a result, project leaders are able to draw resources from any of the design facilities. Intel regarded such flexible resource availability for the design and development of its products as a source of competitive advantage.

During the global architecture development, the team is usually colocated at the *home site* specializing in the chip type. During Phase 2, it is possible for the team members to then work from their respective facilities. In Phase 3, when the designs are integrated, it is necessary for the relevant team members to be colocated at the *home site*. The final phase, Phase 4, occurs at California site, where productization and manufacturing preparation of the design takes place.

DSM Development: It was recognized that a pure product-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 (see Fig. 15) and then the key processes in the development of each of the units were added (see Fig. 16). 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.

A review of the relationships showed that most A ratings existed 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 colocated. The other A ratings occur during chip integration phase (Phase 3) when all the team members are colocated. 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 colocated. Hence, any big revision arising from these interactions/dependencies should be manageable. Similarly, most of the B-rated interactions/dependencies occur, either, during Phases 1 or 3 (when the team is colocated) or within the core and uncore units. Thus, they can be managed within colocated teams.

Key Insights from the microprocessor DSM include the following:

1) The formation of unit-based teams is obvious as most interactions/dependencies exist within the core or uncore unit after Phase 1.
2) Significant efforts in Phase 1 (approximately 50% of the microprocessor design time) ensure that units can be developed independently thereafter, till the final phase of chip integration (Phase 3).
3) During Phase 2, individual unit teams can continue design work independently, and need not be colocated 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.
4) Chip integration (Phase 3) does require the team to be colocated. However, the total team strength is quite reduced at this phase since limited representation from the respective unit teams would suffice.

D. Cessna Aircraft: Supplier Codevelopment

Cessna Aircraft (Cessna) is the world's leading designer and manufacturer of light and mid-size business jets, utility

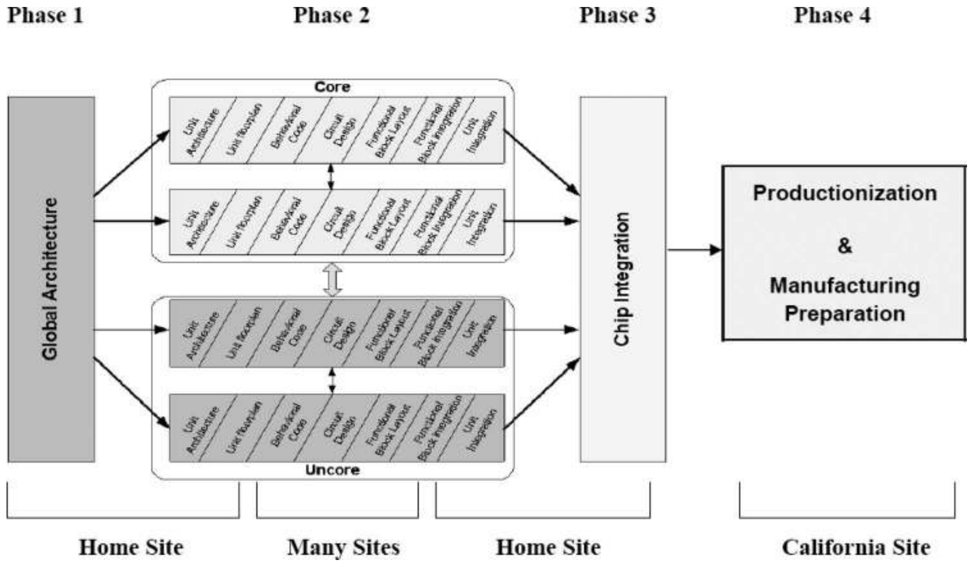

Fig. 14. Intel: microprocessor design and development.

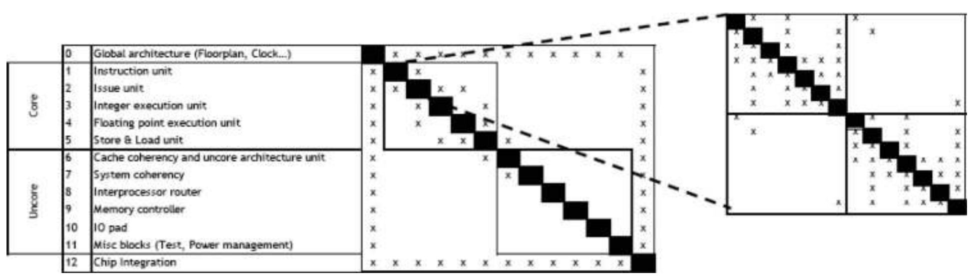

Fig. 15. Intel: DSM summary by chip.

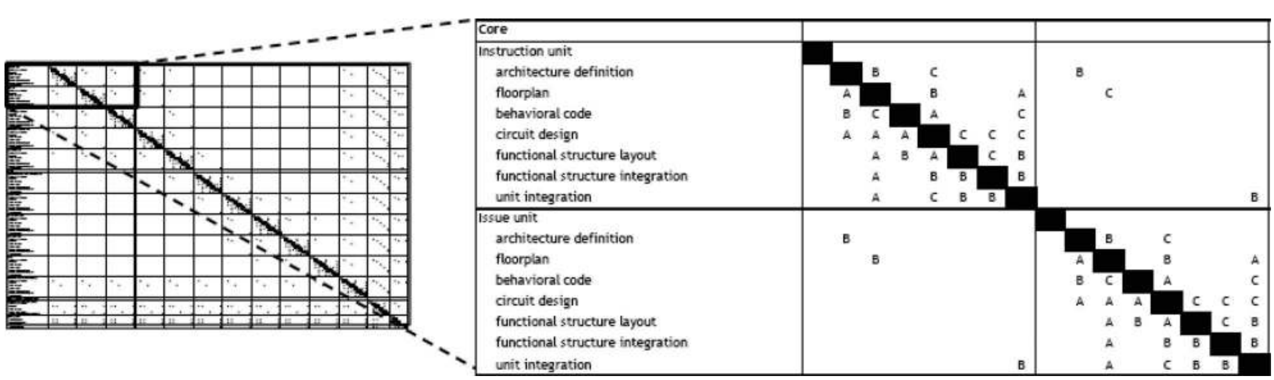

Fig. 16. Intel: Design and development DSM.

turboprops, and single-engine piston aircraft. It is part of the $10 billion Textron group, and is headquartered at Wichita, KS, where it also has its main manufacturing facility, and engineering and PD center. Additional manufacturing facilities are located at Independence, KS, and Columbus, GA. Cessna's aircraft design and development activities are vertically integrated; most design efforts for aerodynamics, structures, and systems integration, and most of the product-level testing are 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 codeveloping 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, it 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 led Cessna to select a second source for the production of

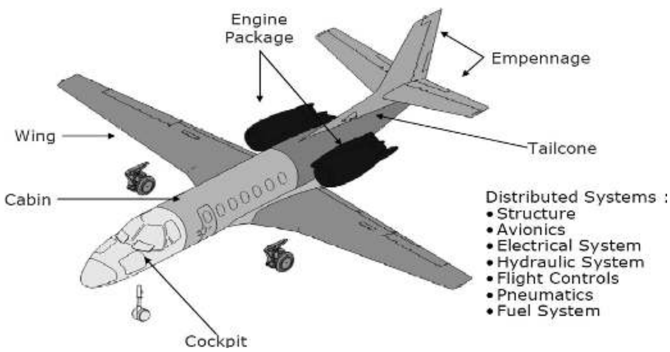

Fig. 17. Typical aircraft sections.

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): In 2004, Cessna foresaw a favorable business cycle trend. However, their internal assessment revealed that the growth opportunities and targets (capacity and cost benefits) could only be met through outsourced design and development (not just build-to-print). However, they decided to retain product architecture development and system integration in-house so that the brand DNA would not be affected.

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. Cessna joined this initiative. Soon they had 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. Cessna was operating under a small-scale GPD model wherein a supplier's employees, colocated 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/subsystem design and development capability within a few years.

System Architecture-Based DSM: 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. 17). The functional systems are distributed throughout the aircraft, touching almost all sections. Similarly, each section contains elements of most of the functional systems.

We started with a section-based DSM. The aircraft can be divided into six different "section-based" systems: cockpit; cabin; tailcone; wings; empennage; and engine package (see Fig. 17). Each of these sections comprises structural subsystems/components that are unique to that section, e.g., shell and structure in the cockpit and functional systems, and certain functional systems that have a significant role within them. These were included in the DSM (see Fig. 18). 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 colocated.

Key Insights: As Cessna expands the development work content and quantum at the GTC and other offshoring initiatives, they could see more suppliers getting involved (either the non-specialized jobs with the supplier's employees at the GTC or through system/subsystem development with offshore suppliers). We outline certain challenges that Cessna needs to be prepared for.

*Co-Location:*Clearly, suppliers providing design capabilities will play a key role in Cessna's development efforts in the future. The strong dependencies of each of the systems/subsystems on the product architecture (as evidenced from the DSM) clearly point toward colocation of the suppliers' engineers with Cessna engineers, at least in the early part of the program when the package and specifications are developed. Subsequent colocation would depend on the level of interaction required. The DSM would need to be expanded to identify the relevant interactions that would require colocation.

Systems Interactions: The DSM shows interactions among functional subsystems—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. Clear roles and responsibilities (R&R) would need to be developed in that case.

*Culture:*Cessna follows the standard Textron seven-stage new products and services introduction (NPSI) process. In a 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/subsystems 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 purely based on functional lines, e.g., electrical, pneumatics, etc, and in-line with the sourcing strategy

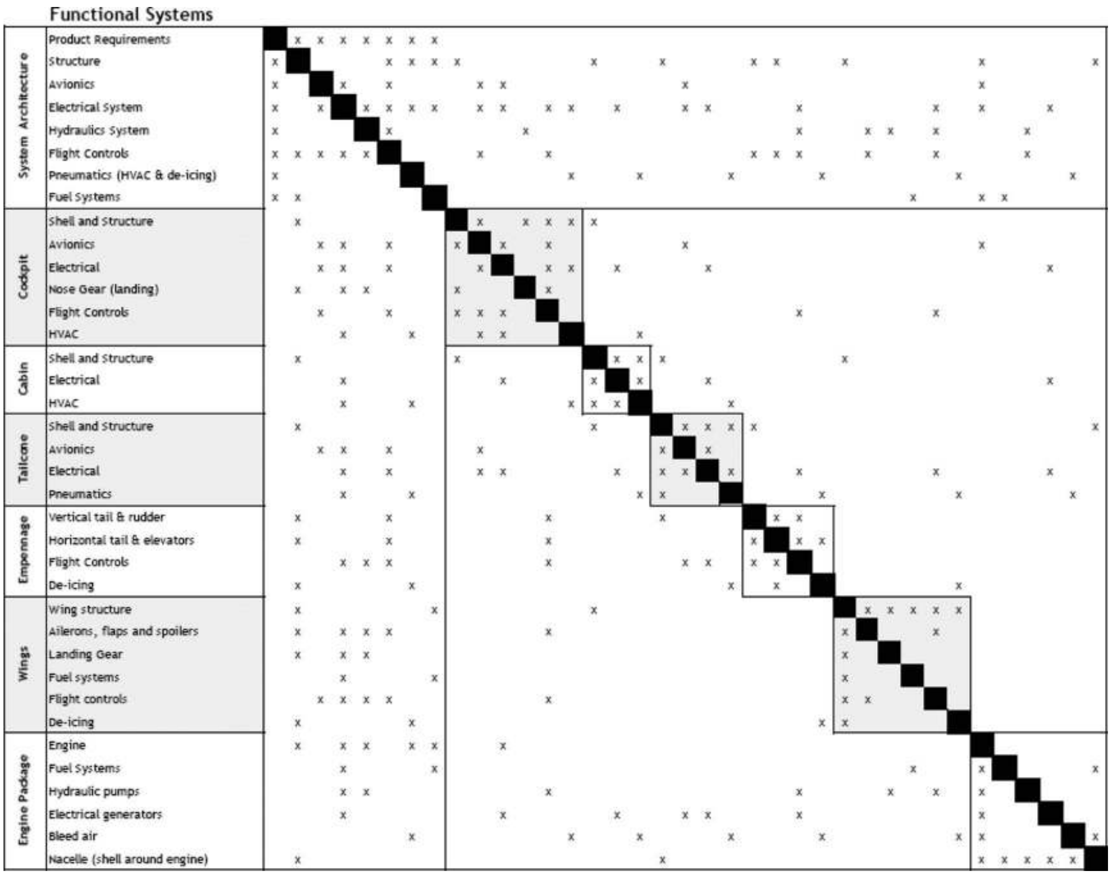

Fig. 18. Cessna: system-architecture-based DSM.

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.

E. Honeywell-Aerospace Division: Task-Based Offshoring

Honeywell International, Inc., is a $31 billion company involved in aerospace, automation and control solutions, specialty materials, and transportation systems. The aerospace division has design and development centers located at several U.S. product sites. This case study focuses on Honeywell Aerospace's avionics operations. 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. The Advanced Manufacturing Engineering (AME) group was created within the Aerospace Integrated Supply Chain in 2005 with the charter to drive down program costs by enhancing collaboration between different participants of the PD process.

GPD Dilemma: 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 coordination efforts will all be considered with any decision AME makes regarding offshoring. The AME group was considering three location options for Honeywell Aerospace's design and development activities:

1) *Local:* current site, close to/near other departments that they need to collaborate with, e.g., Phoenix, New Jersey;
2) *Medium Cost:* close to current location, with close time zones, allowing certain "customer-constrained" jobs to be moved there; cheaper labor costs than local, e.g., Puerto Rico, rural United states;
3) *Low Cost:* distant location with cheapest labor costs, e.g., India, China.

Any location option that AME chooses will involve various costs like: 1) labor costs related to manpower (time in hours); 2) coordination and collaboration costs related to the time spent carrying out tasks, which involve information sharing/transfer; and 3) fixed costs related to setting up new facilities, hiring and training, etc.

There are likely to be constraints of the type: 1) potential capacity (manpower) at off-shore locations; 2) AME tasks that are required to be executed locally; and 3) AME tasks that need to be colocated with other tasks (including non-AME tasks).

Decision-Making Approach: Each option that the AME group was contemplating had 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 coordination and collaboration time, and therefore, add costs. Honeywell had to ensure that an appropriate trade-off, such as lower labor costs against higher coordination and collaboration costs, was achieved prior to offshoring

	Local	Medium Cost	Low Cost
Local	represented below		
Medium Cost			
Low Cost			

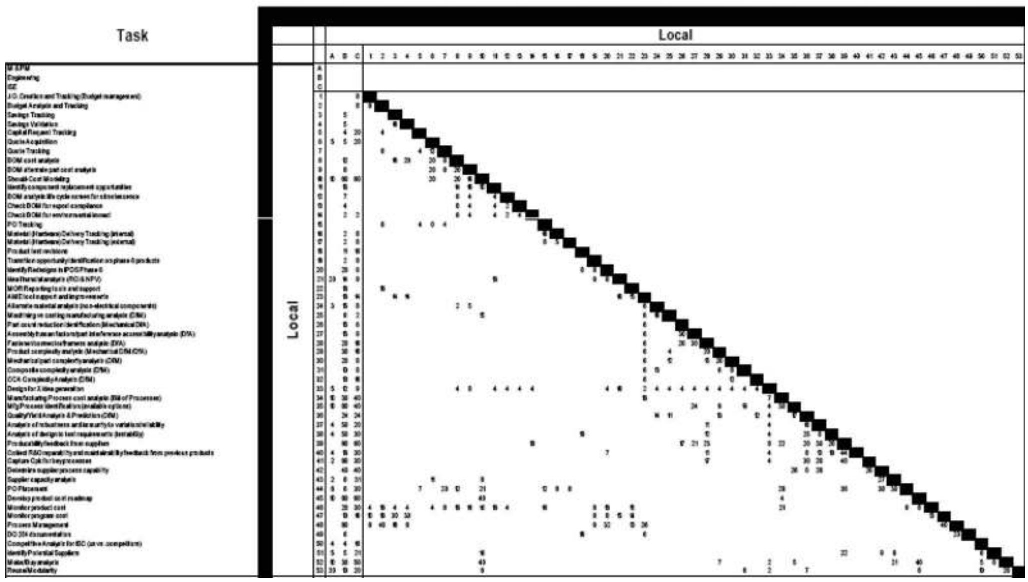

Fig. 19. Honeywell: task-based DSM (structure).

certain tasks. The AME group went through the following steps to determine the tasks that could be offshored.

Step 1: A full list of tasks that AME is responsible for carrying out was generated. Tasks that had to remain onshore were identified, while groups of tasks that needed to be colocated were bundled as single tasks.

Step 2: A (numerical) DSM was developed (see Fig. 19). 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. 19. The rows (and columns) list each of the AME tasks that could be offshored, 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).

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 (coordination time in hours per month). The coordination time between task *Should-Cost Modeling* and engineering is 60 h when this task is done locally (shown as A in Fig. 20). Similarly, the coordination time between tasks *Should-Cost Modeling* and *Quote Acquisition* is 10 h when both the tasks are done locally (shown by B in Fig. 20), but increases to 15 h when *Quote Acquisition* is done in a medium cost country (shown by C in Fig. 20). 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 aforementioned steps, Honeywell was able to identify tasks that could be offshored 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).

V. Collating Cross-Case Patterns

The data from the case studies were very rich and allowed analysis of cross-case patterns [32]. To address the research questions, we utilized information on three key constructs: GPD intent; organizational form of GPD; and decomposition methods. Collating the information from the case studies for each of these constructs, and then observing their relationships, we differentiated between the approaches adopted by the respective firms using the cell design [32].

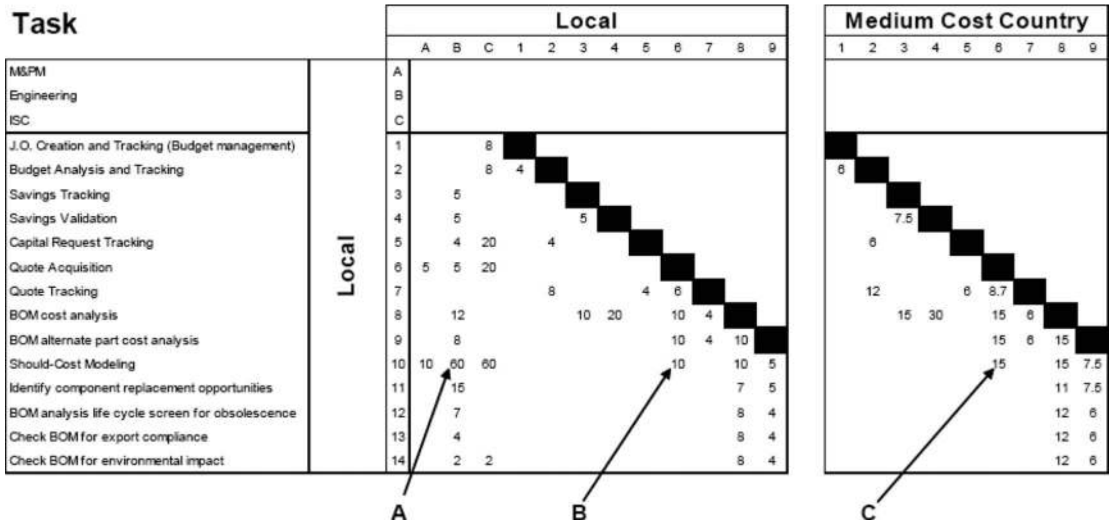

Fig. 20. Sample DSM cutout.

A. GPD Intent

Our cases had been selected (see Fig. 7) based on GPD intent to include both competence seeking or arbitrage (cost savings) [1], [2]. However, during the case studies, we observed that some firms were also pursuing GPD as a development capacity hedging option. We summarize the GPD intent for the five cases in Fig. 21. We had selected PB and Intel as the cases of firms that pursued GPD seeking competencies (Intel was also pursuing cost savings). However, we observed that they were pursuing different types of competencies: while PB's GPD arrangement with Canon was based on dependence for printer technology development and hence critical toward delivering PB's products and services (*complementary knowledge*), Intel set up competence centers globally that supplemented its existing development competencies (*incremental knowledge*) and also translated into cost savings. Such competence centers supported cost savings through arbitrage and successive improvements in products and processes.

Similarly, amongst the firms that pursued GPD for cost savings, significant differences in approaches were observed. Honeywell offshored critical tasks (and hence setup subsidiaries), Danaher Motion only offshored "commodity engineering" tasks, and Cessna offshored a mix of the two. Danaher Motion and Cessna used offshoring as a development capacity hedging opportunity also (offshoring "commodity engineering tasks" supported this).

B. Organization Form of GPD

The firms studied had approached GPD in different ways. We analyzed these approaches (see Fig. 22) through the 2 × 2 make-buy in–out matrix of Section 1 (see Fig. 1). We observed that Intel and Honeywell had opted for captive centers as the PD tasks offshored by them were firm specific and they were looking at developing the corresponding capabilities at the offshore location. On the other hand, Danaher Motion and PB had opted for outsourcing their offshore development work for different reasons: while Danaher Motion sought a supplier

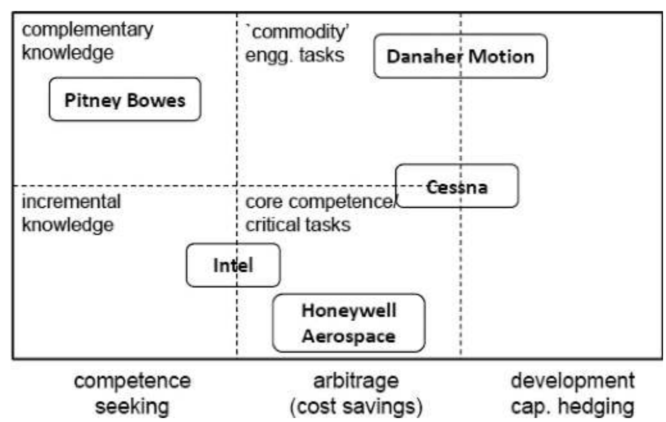

Fig. 21. GPD considerations.

to provide arbitrage and hedging benefits, PB needed to find a supplier to meet a key competence gap in their PD efforts. PB's efforts were more of a case of knowledge sourcing [38] with offshoring being a happenstance. Textron (Cessna) had opted for a hybrid model wherein the supplier was used for hedging development capacity and was utilized only for "commodity" engineering tasks.

C. Decomposition Methods

As discussed earlier, it is very difficult to offshore the complete development of CES. Instead, it is pursued in phases/stages, as observed in the case of Danaher Motion and PB. Decomposition of the CES needs to be done to identify the offshoring content for each phase/stage. We observed different approaches to decomposition, leading to respective DSMs, in the various case studies:

1) *Danaher Motion:* process (Phase 1) followed by product (Phase 3) decomposition;
2) *PB:* product decomposition;
3) *Intel:* product and process decomposition;

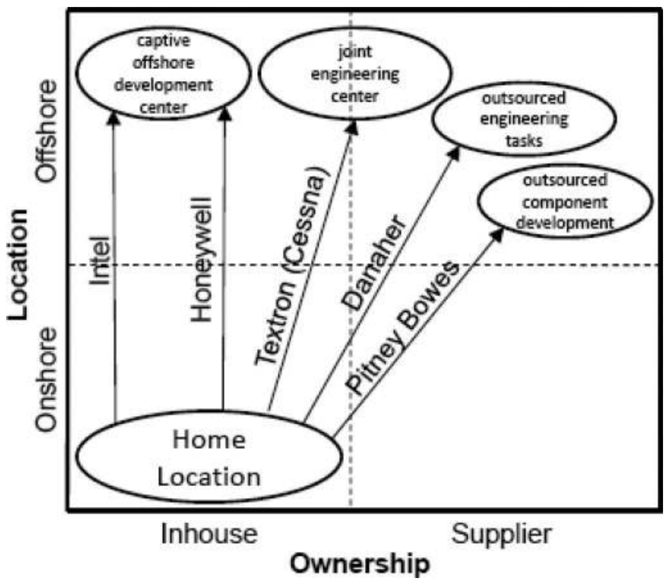

Fig. 22. GPD approaches.

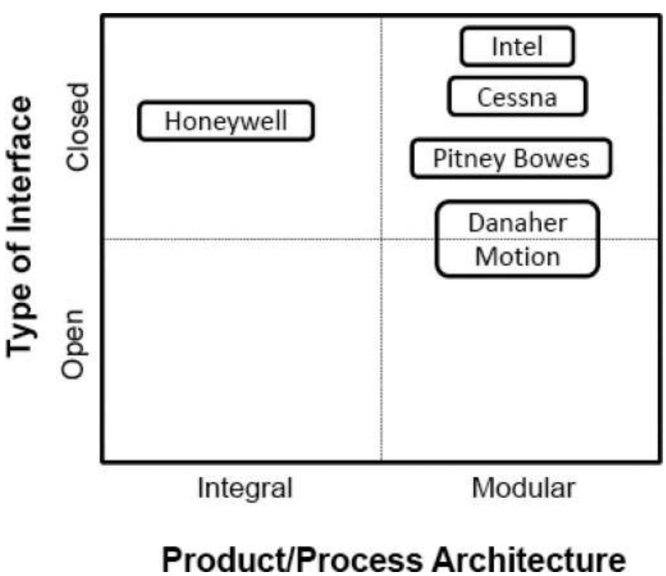

Fig. 23. Architecture assessment and type of interface.

4) *Cessna:* product (section and function) decomposition;
5) *Honeywell:* process (task) decomposition.

The type of decomposition was influenced by the GPD intent and we discuss this in the next section.

In Danaher Motion's case, we observed that the offshore development supplier was exploring alternate locally available "more efficient" solutions. This was possible due to the presence of "open" interfaces. The modularity/integrality of the system [25] and the type of interfaces prevalent after the decomposition exercises (see Fig. 23) are important aspects of system architecture, particularly for CES. Honeywell had an integral architecture, where each task was tightly coupled with others (represented by the coordination needs). On the other hand, the other firms had "relatively" modular architecture wherein certain development tasks could be performed with limited coordination needs across locations. Following Fujimoto [29], we differentiated the types of interfaces as open or closed. While closed interfaces are specific to the product or the firm, open interfaces are common/standard in the industry, in which the firm operates, thus providing an opportunity to seek alternate solutions, e.g., Danaher Motion. On the other hand, PB had well-defined interfaces between the modules. However, these were closed and specific. The open interfaces in their system, e.g., electrical connectors, were within the scope of the offshored development efforts, rather than at the module level.

VI. Process Model for GPD

In the previous sections, we described our case studies and thereafter identified cross-case patterns with respect to our identified constructs. In this section, we connect our observations across the constructs [32] to first answer our research questions relating to the influence of GPD intent on the organization form and decomposition methods that firms need to pursue. We then use these inferences in suggesting a process model that firms pursuing GPD may follow (the latter part of our research question).

A. How Does the GPD Intent of the Firm Influence the Organization Form (Ownership) That the Firm Should Pursue? How Does the Decomposition Method Relate to the Firm's GPD Intent?

We collate our findings, from the previous section, on GPD intent and organization form, and on GPD intent and decomposition method in Fig. 24.

Based on the collated data, we infer the influence of GPD intent on the organization form and decomposition method that a firm needs to follow (see Fig. 25). We discuss it for each identified GPD intent.

Complementary Knowledge: As evidenced in the case of PB, an offshore supplier (Canon) was essential for the development of their product/system. Such competence (complementary knowledge) when residing with an offshore supplier is the case of outsourcing for knowledge [38], where the offshore location is a happenstance. Establishing an offshore captive facility for such complementary knowledge is difficult in such circumstances. Therefore, it is important for the firm to establish a fluent relationship with the supplier (such as that between PB and Canon). In such cases, it is a component/module/subsystem, whose development is done at an offshore location and hence product-based architecture decomposition needs to be done.

Incremental Knowledge: Intel established offshore development centers to benefit from local available talent who were expected to contribute toward product and process improvements. Thus, they were offshoring for incremental knowledge/competence as the development tasks offshored were also being done at their home-based development centers. Since most such development work tends to be firm specific, firms tend to form captive development centers (like Intel). Further, such offshoring progresses in steps, thus requiring two sequential architecture decompositions, first process and then product. In most of such cases, the system architecture development and system integration related

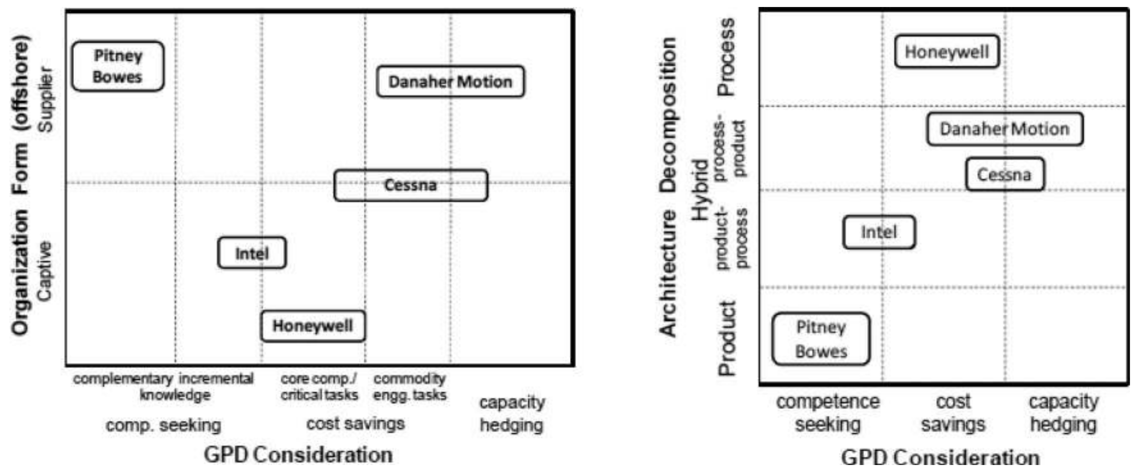

Fig. 24. Collating case evidence of GPD intent, organization form, and decomposition method.

GPD Consideration		Organ. Form (offshore)	Architecture Decomposition	Case Example
Competence seeking	complementary knowledge	supplier	product	Pitney Bowes
	Incremental knowledge	Inhouse / captive	process, followed by product	Intel
Arbitrage (cost saving)	core competence, 'mission-critical', firm-specific work	inhouse / captive	process, product, or hybrid	Cessna / Intel / Honeywell
	'general' or 'commodity' engineering work	supplier	process, product, or hybrid	Danaher Motion / Cessna
Hedging (development capacity)	flexible engg. development workforce	Inhouse / captive or supplier	process, followed by product	Danaher Motion / Cessna

Fig. 25. Influence of GPD intent on GPD organization form and decomposition method.

tasks (see Fig. 2) are not offshored, and the tasks offshored relate to specific component/task development (it takes significant time and confidence before either system architecture development or system integration tasks are offshored).

Core Competence, "Mission Critical," Firm-Specific Development Tasks: Firms that pursue GPD for arbitrage (cost savings) establish captive development centers when the offshored development tasks are related to core competence, or "mission-critical," or firm specific. We observed this in the cases of Cessna, Intel, and Honeywell. Even in their supplier plus captive offshore center, Cessna ensured that "mission-critical" development tasks were performed by their own staff (captive). In such offshoring decisions, the decomposition method pursued may be product, process, or hybrid of the two, and will depend on arbitrage aims. Each case (Cessna, Intel, Honeywell) had a different decomposition approach.

"Commodity" Engineering Development Tasks: Invariably, an offshore supplier would be involved as the development tasks offshored would be very "commoditized" and there would be no risk of loss of core competence or firm-specific information, etc. This was followed by Danaher Motion and Cessna. Since arbitrage (cost savings) is the sole motive here, identifying the right development task for offshoring is key, and hence the economic analysis will drive the choice of decomposition method: process or product or hybrid. Further, in such cases, the presence of open interfaces helps in identifying alternate solutions that may be available at the offshore location.

Hedging/Flexible Development Workforce: The organization form in this case would depend on the types of development tasks that are offshored. Both Danaher Motion and Cessna used suppliers to avail the development capacity hedging. In both cases, it required the presence of highly flexible and multi-skilled development workforce. Such workforce was required to be made available by the offshore supplier in the case of Danaher Motion (since they had to work across different group firms) and as a part of the employed workforce for Cessna (as they performed different types of development tasks based on development work load). Since the workforce will be required to be skilled to perform different development tasks, process-based architecture decomposition needs to be done first (as the identified development process has to be such that it can be performed across components/subsystems by the workforce). This is followed by a product-based architecture decomposition to identify the components/subsystems for offshoring.

B. How Should a Firm Pursue its GPD Efforts?

In the earlier section, we developed inferences regarding the GPD organization form and the decomposition method, as influenced by the GPD intent of the firm. In this section, we incorporate the earlier findings to address the last part of our research question: how should a firm pursue its GPD efforts? We discuss this in three parts: first, we develop the decision steps that a firm takes to identify its GPD structure; then, we incorporate this to propose a process model that firms can adopt for GPD; and finally, we discuss the staged process through which a firm may expand its offshored content.

Identifying the GPD Structure: The GPD structure identifies where and who does each development activity (see Fig. 1). This is largely influenced by the GPD intent (see Fig. 25). In Fig. 26, we identify the steps that the firm should follow.

All our discussions in this paper have centered on firms that are pursuing GPD to augment their home-base capabilities [4]. There are also firms that do GPD to meet specific needs of

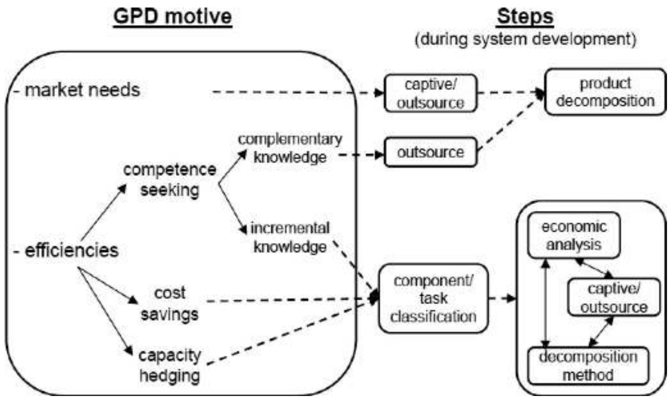

Fig. 26. Decision steps toward identifying the GPD structure.

the offshore markets needs. The offshore development facility for performing these development activities may be captive or owned by a supplier based on core competence, business criticality, economic considerations, etc. In both cases, firms pursuing GPD to meet market needs or seeking complementary knowledge, the (basic) content for offshoring is well known. Hence, the product decomposition activity happens after the organization form is decided. The capability at the offshore captive unit/supplier will influence the decomposition efforts and the scope of supply (beyond the basic content) thereafter.

On the other hand, when the GPD intent is to seek efficiencies (other than complementary knowledge), the firm needs to first classify each component/PD process/task development to a quadrant of Fig. 1, differentiating between those that the firm is willing to consider for offshoring from those that it is not, and similarly for outsourcing. This identifies the basket of tasks to be considered for offshoring. The final offshoring content is the output of an iterative process involving the decomposition method, corresponding economic analysis, and the captive/outsource decision. At times, one or more of these factors may be fixed/constrained by the firm, e.g., Cessna had decided that the "mission-critical" tasks would be captive, or Intel who had decided on establishing a captive development center, and then the iterative process would involve the other factors.

Process Model: Fig. 2 identified the process for development of CES. In GPD, the offshore development activities primarily occur during the component development phase, which requires some related steps to be undertaken during system architecture development phase. We suggest, building on the case studies, a process model (see Fig. 27) for firms as they embrace GPD.

The key decision point in GPD is identifying the offshoring content (GPD structure). This is determined during the system architecture development phase. Thus, though the home/base location or the central R&D function has complete responsibility for this phase, offshore centers (captive and suppliers) may be involved, providing inputs during concept development and system design (shown as areas X and Y, respectively, in Fig. 27). The GPD structure is developed during this phase and is influenced by GPD intent, decomposition method, economic analysis, etc., as discussed earlier. The proportionate areas of X and Y during the system architecture development phase change based on GPD intent, complexity of the CES, etc., e.g., the area increases if the GPD intent is market needs or competence seeking, where the inputs from the offshore development center is significant during system architecture development.

Though there are inputs from offshore development centers, the system architecture approval is retained at the home location or the competence center (observed during our case studies, e.g., Intel, Cessna, PB). Firms should retain this responsibility in-house 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., ensuring final product integrity. Transferring this decision to an offshore engineering center may lead to serious implications on quality and development time. In the 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 PD cycles and numerous product iterations. This practice is demonstrated in the DSMs of PB and Intel (see Figs. 12, 15, and 16).

Subsequent to system architecture development, the respective component/task development activities take place (onshore and offshore). This involves appropriate exchange of information as required by the architecture. Thereafter, development progresses as per the requirements outlined during the approval stage of system architecture development phase.

Similar to the architecture development phase, the responsibility of the final phase system integration is retained at the home location/competence center. Again, in this phase, there could be some inputs from the offshore centers (Z), but the final system integration approval responsibility remains with the home location/competence center and is a core competence.

Staged GPD: We just suggested a process for a firm to initiate offshoring of development activities. However, firms, specially those seeking efficiencies, constantly explore opportunities to expand their offshoring content. We observed that Danaher Motion, in their second stage of outsourced offshored engineering, were exploring at expanding the offshore development responsibilities at the GDC to include complete component and subsystem development. Similarly, PB's system architecture offered them an opportunity to get complete subsystems developed by external suppliers instead of the component level development that they were engaged in. Cessna's first attempt had not been very successful, but they were very satisfied with their corporate-led GTC center and were looking at expanding their offshore work there. These observations align well with Eppinger and Chitkara [1] who state that firms should start their GPD efforts through task offshoring, followed by component development offshoring, and then subsystem development. Success at each of these levels depends on the relationships between the development tasks already offshored and the next stage of development responsibilities, i.e., their architectural relationship, the flow of learning effects, etc.

While the aforementioned steps appear coherent, we would suggest an initial "exploring, experiencing, and learning" step before the aforementioned steps of GPD expansion, similar to our observations in the Danaher Motion and Cessna case studies. Danaher Motion's initial offshoring experience consisted of

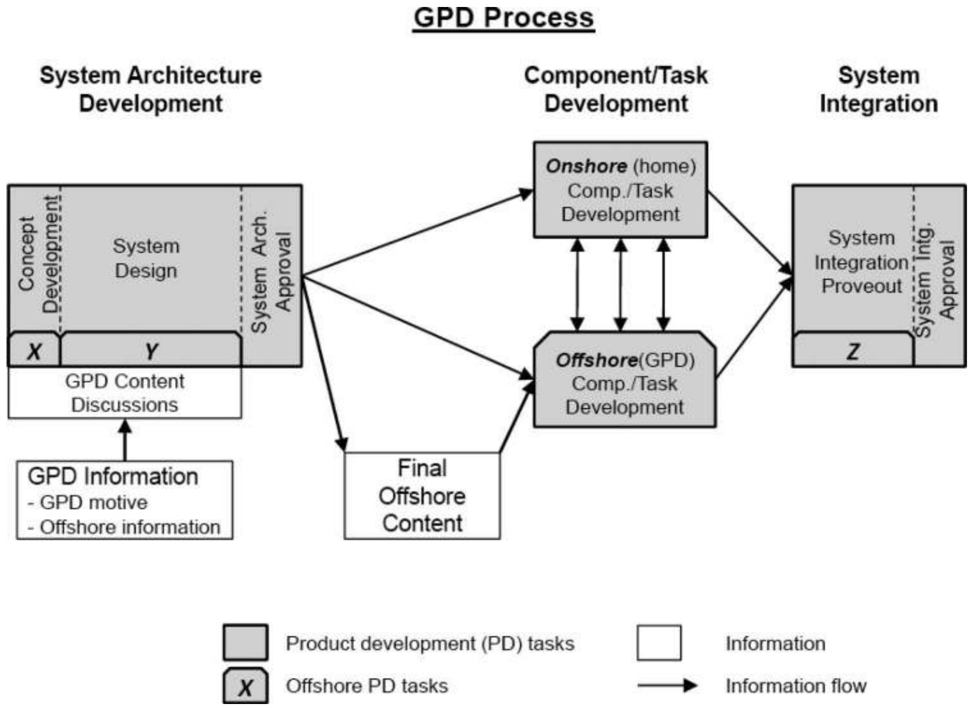

Fig. 27. Suggested process model for GPD.

an "over the wall" approach wherein the development of a set of tasks was passed to an offshore supplier and after "not satisfactory" experiences, was brought back onshore (insourced). In their next offshoring attempt, they transferred the same content but after two additional steps: joining their corporate effort and working with other group firms; 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 were challenged in the development effort, particularly with respect to PD practice and PD standards. However, they believed that it was a learning experience for them and they would not hesitate to use the same offshore supplier again.

These 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 in-house development facility. The "payback" from offshoring design and development activities is unlikely to be immediate and requires patience on the part of the firm.

VII. Potential Research Opportunities

We had identified the gap in existing academic literature that we address in this paper. Being nascent research [8], we used case studies to infer certain practices that firms may adopt while offshoring development activities and also suggested a process model for these firms. There exist research opportunities to mature this research by developing hypothesis for each of the inferences (see Fig. 25) and testing them using larger samples. Further, we observe some similarities in the decomposition methods inferred for various GPD intent. Mature GPD practices may be documented and contrasted against these inferences to help support them. Besides, our observations from the cases also provide a number of options for further research. We classify them along the known constructs of PD performance: architecture; cost; timing; and quality.

Architecture: Novak and Eppinger [39] have 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. On similar lines, considering PD activities, a line of research can explore the relationship between design complexity and DPD, extending it for CES decomposition, i.e., how easy or difficult is it to decompose a CES so that GPD of subsystems/components can be pursued? Building on the information processing view that architectural knowledge tends to become embedded in the structure and information processing procedures of established organizations [27], it may be worthwhile to research if GPD opportunities (either pursued due to adaptation or arbitrage reasons) drive architectural changes, and if they do, how does that impact the firm?

Sosa *et al.*. [40] 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. This finding can be extended to research for changes in alignment with GPD: do teams in different locations (with their cultural, communication, time zone challenges) have the same intensity of communication, or if it changes, how does it 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 establish a model to predict the change based on these causes?

Cost: As discussed in the paper, the information flows, linkages, dependencies, etc., present between the identified in-house and outsource processes/subsystems/parts challenge offshoring efforts, particularly for CES. 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 subsystems/components. Such measures/constructs can develop quantitative approaches to help prioritize and optimize GPD efforts for maximum benefits (e.g., Intel and Honeywell cases).

Timing: Most firms involved in CES follow a stage-gate process [41], where the detailed launch time plan incorporates resource availability. In GPD, the resources may be available, but come with added variability of different locations, culture, communication methods, time zone differences, etc. This could affect PD timing, time to market, etc., and is an area of research. It could explore various aspects: Does the development time change? 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 PD time for the subprocesses/subsystems 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)?

Quality: Though a firm may pursue GPD for arbitrage, it is unlikely that they would 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 their initial GPD experiences, though they are willing to work with the same supplier again. Quality dissatisfaction in GPD could arise due to the inability of the GPD locations to meet home-base requirements in terms of cost, specifications, timing, communication issues leading to misinterpretation, cultural differences, etc. Considering that GPD is becoming more common now, there are opportunities to research the determinants of quality in GPD and develop appropriate quality parameters, which can be used during GPD assessment.

Many of the aforementioned research ideas, perhaps, allude to a single GPD action by the firm. In practice, a firm is likely to start slow, outsource a part of a process or a subsystem, 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 outlined the possibilities for better utilization of the GDC; however the final decision to do so would depend on Dover's satisfaction of the performance of the GDC in Phase 2 and the corresponding benefits that the GDC would provide in Phase 3. Similarly, PB, through product decomposition, has been able to outsource the manufacturing of modules. These suppliers may have the capability to progress to designing the modules hereafter (Canon is already designing the printer technology and the finishing module is a natural step forward for them). Also, Cessna will look for higher utilization, through a mix of in-house/outsource, from the GTC. Researchers can explore how system architecture can progressively identify subprocesses/tasks or subsystems/components for outsourcing or offshoring, perhaps by developing a suitable real option structure [42], [43].

GPD is emerging as an important opportunity for firms developing CES. While the first wave of GPD is likely to be driven by arbitrage or adaptation considerations, soon aggregation on regional basis may take over. Though earlier literature has covered multinational R&D, they have focused more on research activities. Simultaneous development as envisaged in GPD has received scant attention in literature. We have outlined some of the relevant literature on R&D networks. We have 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 provide the appropriate seeds for further research and related developments in practice.

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