Coordinating Hardware and Software Development: Evidence of Success Factors

By

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Abstract

This thesis provides evidence on the factors that lead to success in coordination of concurrent hardware and software development in complex electronic system design. The success measures used were related to project cost and schedule adherence, product functionality and total development time.

With the purpose of obtaining a better understanding of how hardware and software coordination takes place in practice and what the managerial concerns around this topic are, two case studies with local telecom firms were carried out. Data from the case studies were used to inform the theoretical model used and data gathering method. Subsequently, data were gathered on 28 projects and put together with other 21 previously gathered by Koch (1997) to form an aggregate sample.

The results from the analysis of the new sample and of the aggregate sample showed that: number of levels to common report, extent of shared design documents, physical distance and group-based evaluations between hardware and software developers, correlated with project cost, schedule and product functionality goals. Decreasing physical distance and the number of levels to common report were found to have significant effect in reducing product development time.

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1. Thesis Overview

Coordination of hardware and software co-design has become a significant part of the product development process in all industries where complex electronic systems are developed. In a search for competitiveness, flexibility and cost reduction, system electronic suppliers have increasingly incorporated microprocessors, ICs (Integrated Circuits) and ASICs (application-specific integrated circuits) in their products. This has lead to a significant increase in the amount of concurrent hardware and software development that these companies undertake. The coordination of this concurrent hardware and software development constitutes a major challenge in achieving product success. These challenges are further increased by the fact that today's high-paced technology economy demands shorter product development cycles as early-entrant competitors obtain the benefits of being first to market, gaining higher revenues and higher profits than latter-entrant competitors.

There has been very limited research to date on these hardware software (HW-SW) coordination problems. One significant study is that carried out by Koch (1997). Her study forms the basis for this current research. Her theoretical model has been used in adapted form, and her sample combined with a new sample to form a larger aggregate sample.

The product development time literature (Smith and Reinertsen 1998 , Grinter, Perry and Herbsleb 1999, Callahan and Moretton 2001) provides us with abundant management

approaches for reducing product development time. The conclusions of this literature are, among others, that early customer and supplier involvement in the development process, cross-functional teams, supplier involvement and overlapping development activities are critical factors to reduce product development time. This literature is used in the current study to form a theoretical model for testing how hardware and software coordination in the development process can influence product development time.

This thesis provides evidence on the factors that lead to success in coordination of concurrent hardware and software development in complex electronic system design. The success measures used were related to project cost and schedule adherence, product functionality and total development time.

With the purpose of obtaining a better understanding of how HW-SW coordination takes place in practice and what the managerial concerns around this topic are, a set of two case studies with local telecommunications companies were carried out. Then, a questionnaire based on the Koch (1997) study and the case study results, was sent to 92 companies in the high-tech sector. Twenty-eight responses were received and put together with 21 previously gathered by Koch (1997) to form an aggregate sample.

Some of the conclusions of Koch (1997) on HW-SW coordination were corroborated, and additional statistically significant results were obtained. The effects of these results in reducing product development time were then tested through correlation and linear regression analyses, with some statistically significant results.

The current study shows that the number of levels to common report, extent of shared design documents, physical distance and group-based evaluations between hardware and software developers, are correlated with project cost, schedule and product functionality goals. Physical distance and the number of levels to common report were also found to have significant effects in reducing product development time.

This research will help project, hardware, and software managers better understand how the proposed hardware and software mechanisms can improve project success and their effect in reducing product development time.

2. Literature Review

Since digital electronics have made possible the incorporation of software programs in ICs to reduce the size and cost of electronic systems, electronic system design has become more complex and demanding. A significant complication for electronic system suppliers is that the processes to develop hardware and software for these systems are significantly different. As well, companies are required to deliver products to the market at a faster pace.

Because of the increasing amount of software being developed in products, HW-SW coordination is an issue that must be addressed in order to achieve product success and deliver products to the market quickly.

This thesis research fits into a research stream on the coordination of differentiated organizational units that dates to the classic study of Lawrence and Lorsch (1967). Dougherty (1992) articulated well the barriers that build up between differentiated organizational units and impede innovation. Because of the particular nature of the problems that they face and the activities and tools that they use to address these problems, functional specialists within organizations come to see all problems, activities and tools through a functional lens. This leads them to dismiss the importance and difficulty of the problems, activities and tools of other specialist groups.

2.1 R & D Coordination

In the last decade the amount of software developed to enhance functionality of hardware products has increased significantly. Rauscher and Smith (1995) explain how the increase in hardware performance capabilities in copier products from a major manufacturer generated an increased demand for software. This increased demand for software development augmented the need for software developers over that of hardware developers leading to a complicated environment in which both specialties need to interact. The study by Koch (1997) states that: "the environment in which hardware and software developers work is unique and can be problematic during the development stage."

Despite the difference between these two specialties, HW developers tend to be more familiar with software development than SW developers are with hardware development (Rauscher and Smith 1995). Rauscher and Smith also affirmed that software development is a highly technical specialty, and that some software engineers prefer to keep to themselves.

In the study done by Koch (1997), the relationship between developers experienced in both hardware and software design and product success was explored. Contrary to her theoretical model, she did not find that developers with both HW and SW design experience were critical for product success. This outcome does not conform with previous research in other areas of inter-functional coordination such as design and

manufacturing (Rusinko 1992). Supporting her theoretical model, Koch (1997) quotes an engineering consultant as follows: "The best engineers are those who have experience in both worlds, because they understand optimality in both paradigms, and can make educated trade-offs, instead of simply getting into biased matches with their counterpart, making it an ego-based argument."

Hauptman (1990) analyzed a vast amount of literature concerning the development of SW and of "hardware." For Hauptman, "hardware development" meant the development of physical products, i.e., not software. He articulated a number of similarities and differences between hardware and software product development. He gives a simple table that enumerates some relevant differences between hardware and software product development, providing a clear understanding of why coordination mechanisms between the two are important when this development is done concurrently.

Table 1: Comparing SW Development and HW R&D

Dimensions	Software development	Hardware development
Product	Does not break down with use	Break down with use
Manufacturing	Simple replication	Complex transfer
Influence of task type	Increasing difficulty	Complex contingency
Managerial imperatives	Control and discipline for coordination Product Modularity	Optimal communication for technology flow
Techniques and methods	Surgical team, structured design	Organizational design, architecture, information technologies
Role of communication	Coordination overhead Potential threat to product integrity	Vehicle of technology flow
Critical Roles	Project Mangers, designers, programmers, validators	Project managers, gatekeepers, engineers
Effectiveness measures	Individual level Lines of code per unit of labor	Group/ project level Budget, schedule and technical quality.

Hauptman (1990)

How the critical paths in a project evolve over time is significantly influenced by the differences in hardware and software development processes and communication. In particular, Hauptman (1990) investigated the role of communication for productivity in both hardware and software development. He reviewed some findings in the literature that suggest a positive influence of strong information flows in non-software R&D while

at the same time suggesting that an abundant flow of communication tends to interfere with software productivity.

Rauscher and Smith (1995) provided a simple, yet effective example of how HW-SW coordination is critically important in R&D. They described how the implications of selecting either a ROM or DRAM memory to "burn" the software in a particular project could become a critical trade-off between cost and schedule. This example emphasizes the need of communication between the two groups in all the development phases during which important trade offs are to be decided. During HW-SW product development there are different stages in which development is done mostly concurrently; however, at the beginning of the project, HW and SW developers should have abundant communication to agree on the project's specifications. Rauscher and Smith (1995) called the requirement specification phase "the most important phase of software development." In this phase a specification document is created to outline: the HW and SW functions to be performed, functionality to be achieved, and the design constraints. The sharing of specification documents between hardware and software developers in this phase may become a critical success factor in later stages of the product development process.

There is a tight interdependence between hardware and software development that also calls for coordination mechanisms. Each side desires a piece of the other side's completed work in order to test or prove that their own work is viable (Rauscher and Smith 1995).

Thompson (1967) suggested three types of interdependence: pooled, sequential and reciprocal. In pooled interdependence, interdependent units in an organization contribute to the organization while having no direct work interactions. Sequential interdependence is asymmetric. Reciprocal interdependence exists when an output from each unit becomes and input for the other. In the case of HW-SW development, the work outputs of one unit are the inputs for the other. The reciprocal interdependence between them makes necessary a high degree of coordination. Mutual adjustment as described by Thompson (1967) becomes a significant part of the coordination process.

Van de Ven, Delbecq and Koenig (1976) investigated how the variations and interaction in the use of three coordination mechanisms (impersonal, personal and group) were explained by task uncertainty, interdependence and size. Task uncertainty refers to the difficulty and variability of the work undertaken by an organizational unit. Task interdependence is the extent to which unit personnel were dependent upon one another to perform their individual jobs. This paper focused on key propositions of Thompson (1967) and others about coordination at the work unit level of organizational analysis.

Van de Ven, Delbecq and Koenig (1976) found that as task uncertainty and interdependence increased, the use of group coordination (scheduled and unscheduled meetings) increased. These results support Thompson (1967) that as the task encountered by a unit becomes less analyzable and more variable, a great number of mutual adjustments are required among unit members.

To deal with this interdependence, Koch (1997) proposed the mechanisms of both sharing design documents and sharing design tools to a greater extent.

Rauscher and Smith (1995) pointed out how the close interdependence between HW and SW developers can lead to opportunities to blame each other. As a basic approach in solving this dilemma, they suggested creating "we" situations instead of "they" situations. Koch (1997) also emphasized the need to shift from the "us and them" mentality to a "we" mentality if common feelings of unity between hardware and software developers are to be achieved.

Rauscher and Smith (1995) suggested the following possible solutions:

1. Organizing so that hardware and software personnel report to a common leader.
2. Co-locating this combined team.
3. Ensuring that evaluations, recognition and reward systems support mutual accountability.

Some of these suggestions were tested as hypotheses in Koch's work. She proposed that:

1. The number of levels to common report (between hardware and software developers) has a negative effect on project success.
2. Physical distance is negatively related to project success.
3. Group-based evaluations are positively related to project success.

When dealing with decision-making in the HW-SW product development process, software trade offs and feature implementation options may become critical, both in time and cost. Koch (1997) suggested that problem-solving communication should be done at the lowest level of authority in hardware and software teams alike. This means that having the fewest levels to common report between hardware and software developers should increase product success.

Another major challenge in HW-SW coordination is collaboration between different sites. In the global economy, companies have increased the amount of distributed work; mergers, acquisitions, alliances, and market conditions are just some of the reasons why R&D is often done in different locations. Grinter, Perry and Hersbleb (1999) outline methods that companies use to deal with distributed product development related to product structure, areas of expertise, process steps and customization. They also emphasize co-location as a means to facilitate ad hoc communication in support of coordination.

Findings mentioned by Grinter, Perry and Hersbleb (1999) suggest that informal, unplanned, ad hoc communication is extremely important in supporting collaboration. Moreover, their findings suggested that informal communication plays a critical role in coordinating R&D work. They noted that informal communication remains much less frequent between people across different sites than in same-site interactions. Their study reported that placing HW and SW teams in different locations heavily reduces the amount of this communication. These findings suggested that the reduction of physical distance

between hardware and software developers would increase ad hoc, informal communication.

Rauscher and Smith (1995) also emphasized the importance of cultivating software knowledge. They state: "At higher levels, product development managers need a greater knowledge of software technology and management techniques to make effective decisions on the direction of the firm." In complex electronic design this software cultivation should apply not only to management but also to hardware peers. The same should also apply to software developers about hardware knowledge so that mutual understanding about each other's tasks leads to effective-and on-time decisions.

2.2 Product Development Time

In today's competitive economy, product development time is one of the most important success factors in an organization. The business opportunity of being first to market, or to take a product to the customer before a competitor, allows an organization to obtain larger revenues and larger profits as well as to gain early feedback from the market for future development. Also, high-paced technological change leads to shorter product life cycles which, as a result, demand shorter development time of products.

Smith and Reinertsen (1998) pointed out that early customer involvement in the development process, overlapping tasks, and cross-functional teams are important factors in reducing product development time. Furthermore, they affirm that: "One major opportunity and challenge is to overlap hardware and software development and testing. Such overlapping is not natural and will not occur without some specific attention to it."

Smith and Reinertsen also noted the benefits that generalists, rather than specialists, provide to a development team. Their flexibility enables them to move from act to act in the development tasks whenever a critical path is detected. Smith and Reinersten give the following, stating that flexibility leads to speed:

" ...not only should the marketing member be comfortable with a soldering iron, but the scientist on the team should also be able to demonstrate the product to a group of visiting customers or create a first draft of advertising copy if needed."

Typically the pressure to deliver according to a pre-arranged schedule is intense. When distance becomes a communication factor between HW and SW teams product development time may also become affected. During their interviews, Grinter, Perry and Herbsleb (1999) found that developers were much less responsive to coworkers who resided at different sites. Consequently, delayed information flow impacted product development time.

Eisenhardt and Tabrizi (1995) contrasted two innovation strategies: compression and experiential. Compression strategy used the following mechanisms: planning, supplier involvement, use of computer-aided design, task overlap, multifunctional teams and reward for schedule attainment. Experiential strategy used: design iterations, increased testing, shortened intervals between milestones, and project leader power. They found compression most appropriate when product development is a certain, predictable process and can be planned out as a series of steps. They found experiential most appropriate when product development is highly uncertain.

Zirger and Hartley (1996) categorized the determinants of new product development time into three areas: product strategy, development process, and development team structure variables. They found that fast developers had teams that were cross-functional, dedicated to one project, included development time as a goal, and overlapped development activities more so than slow developers.

Callahan and Moretton (2001) explored project management approaches for reducing software development time using a research approach developed by Eisenhardt and Tabrizi (1995) and Zirger and Hartley (1996). They addressed the lack of research on software product development time, using the research literature on development time of physical products as a base. As they stated, "software is pure design—the laws of physics are not constraints" which highlights a major difference between HW and SW design.

Software design is "in the code" so that it is not visible making it hard to use software design as a focal point for development project coordination and integration, unlike many physical designs that can be made visible to all project participants.

Callahan and Moretton (2001) found that product newness affected the determinants of software development time. They also found that supplier, and sales and marketing involvement early in the development cycle lead to shorter development time.

3. Case Studies

With the purpose of better understanding how HW-SW coordination takes place in practice and what managerial concerns surround this topic, a set of two case studies with local telecommunications companies were carried out (Yin 1989).

Several semi-structured interviews were conducted with a project manager, a software manager and a hardware manager working together in a specific project. A review of project documentation was also undertaken for each case study. The case studies and the concerns and implications that surfaced relating to HW-SW coordination are presented in this chapter.

3.1 Data Collection Process

Interviews lasted from a range of 1 to 3 hours according to the interviewee's schedule. Questions about HW-SW coordination included:

1. Were any hardware and/or software developers experienced in both hardware and software fields involved in the product development process?
2. How close (regarding to physical distance) were these two groups located?
3. What type of shared design tools were used for the development of the project?
4. What were the biggest challenges and concerns when developing this project?
5. Were there any lessons learned through this project?

Other data sources included minute meetings, electronic messages and design documents.

3.2 Case Study One

3.2.1 The Company

The source of the first case study is a global telecommunications equipment and solutions company headquartered in London, England. The company's core business is the provision of innovative and reliable optical networks, broadband routing, switching and broadband access technologies and services. The company's aim is to help fixed and mobile telecommunication operators worldwide to reduce costs and increase revenues. It provides a reliable network foundation for the core of the Internet, offering a high quality of service on a worldwide scale.

The company has research and development facilities in nineteen countries, manufacturing operations in sixteen countries, and customers in over 100 countries. Their target markets include: cable and wireless telecom companies, leading Internet service providers, inter-exchange carriers, competitive local exchange carriers, competitive access providers, large enterprises and public network access. The company's customer base includes many of the world's largest telecommunications operators.[1]

[1] From the companies web page

3.2.2 The Project

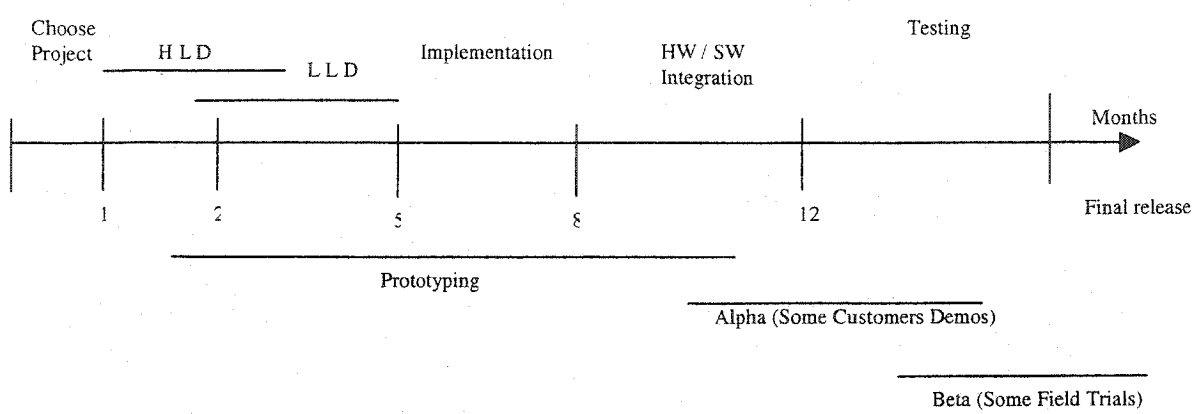
The company has developed an asynchronous transfer mode (ATM) switch platform as their scalable networking solution. This platform is oriented to satisfy the network requirements of global communication companies, large enterprises and next generation service providers.

The case study project was a new hardware and software release for this platform. The objective was to develop a circuit emulation card to transmit voice over ATM. The card supports four ports at OC3 rate. The project was developed addressing the requirements of a large rapidly growing market, where there were some competitors of which at least one had introduced a similar product.

3.2.3 Time Line

The project started in April 2000. The Ottawa Core Team worked in the project plan and after its approval they worked on the High Level Design (HLD). In June-July 2000, after having the first set of specifications of the HLD, the engineers started working in the Low Level Design (LLD); this stage lasted three months. The development process included sequential and overlapping steps (see Diagram 1).

Diagram 1:Company's Number One Project Time Line



The implementation process took them three months; it was an isolated process that lacked full communication with suppliers, hardware, and software departments. Due to the fact that the microprocessors and integrated circuits that they used for its product were generic, the engineers had to learn about the characteristics of these components, even as the vendors were introducing new component releases. The HW-SW integration process turned out to be the most complicated stage of the project. During this stage, there was full communication among all members of the team. Several designs and prototypes that had been built independently in previous stages had to be modified to achieve the desired results. This stage lasted four months. The Quality Assurance Department was also involved in this stage of the process by conducting the first pre-alpha test. The alpha test also included some customer demos. The beta test was also performed at this stage in the process.

The final release due date had to be modified several times because of unexpected delays and problems, especially in the HW-SW integration phase. Finally the product was released after eighteen months of development.

3.2.4 HW-SW Organization

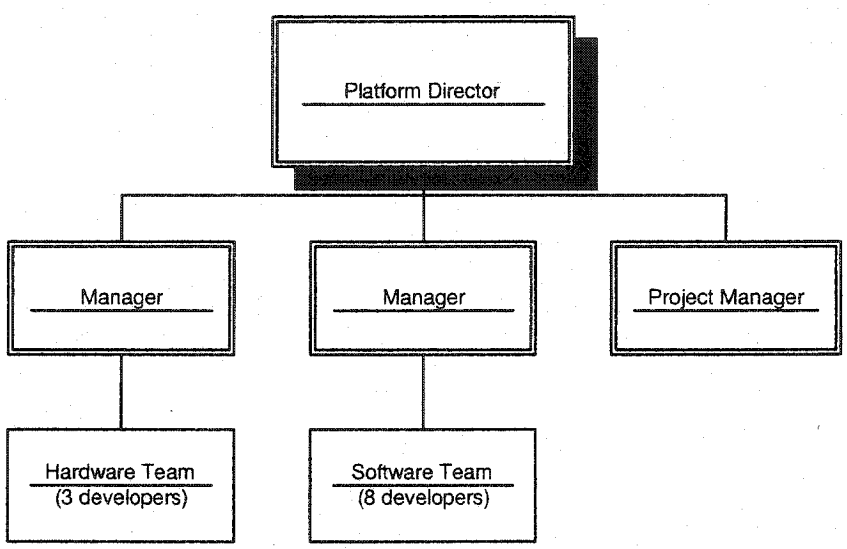
The software group started the early stages of the development process with five people, including the Software Manager. During the project, the maximum number of software developers working concurrently on the project was nine (again including the Software Manager). The Software Manager had worked for ten years in another telecom company in hardware and software fields. Two of the software developers were assigned part time to this project.

The hardware group was comprised of four people, including the Hardware Manager. Two of the hardware developers were assigned part time to this project.

Although none of the developers assigned for this project were experienced in both hardware and software development, one of the software developers was regarded as very hardware savvy and acted as a mentor for junior and intermediate software developers. In the eyes of the managers interviewed, all hardware developers seemed to understand the software issues in question.

The Software Manager was responsible for the software group just as the Hardware Manager looked after the hardware group; both of which reported to a Platform Director. The Platform Director also received reports from the Project Manager whose function was to update the project plan, schedule and prepare meetings, do meeting reports, keep track of the project and identify possible bottlenecks. Diagram 2 represents the organization structure for this project:

Diagram 2: HW-SW Organization Structure in Company Number One



3.2.5 HW-SW Coordination in Review

Since the beginning of the project development process the hardware and software teams shared a project folder on the company's network. This folder contained all project-related documents (design specifications, meeting minutes and the project schedule) and was available to all project participants. The managerial team put emphasis on keeping

this folder up-to-date and it being reviewed frequently by all members on the project development team.

All of the project development team members were co-located next to each other on the same floor within a few steps of each other. "This facilitated a lot communication within members," said the Hardware Manager, "especially when you are building a new team and everybody is new to everybody, this helps in breaking the ice." Formal meetings were scheduled every week and ad hoc, hallway communications sporadically occurred every day.

As hardware and software developers were being staffed for this project, informal communication, team evaluations, and team rewards were maintained by the management group to promote a single team vision. "This was one of our worst challenges in this project, putting the team together and making sure our vision was understood", said the Hardware Manager.

The evaluation system within the company has always been centered on individual performance. Nevertheless, the hardware and software managers promoted team evaluation and recognition for this project. During the early stages of the development process, individual and group rewards were given to the team, including lunches and small economic rewards whenever an important milestone was reached. In the last stages, however, when the schedule became critical and the job most stressful, the company froze this reward system.

3.2.6 Managerial Concerns Around HW-SW Coordination

The management team recognized that ad hoc, informal communication was a critical success factor in achieving a compelling shared vision of the team's goals. However, a major concern for them about this style of communication that in present and future projects, the company's policies and organizational modifications, aimed to deal with the current industry trends, will not support these mechanisms.

According to the management team, the individual and team oriented evaluation and reward system helped in keeping developers focused and positive even when faced with adversity. When this system was frozen, the impact was felt not only by the developers but by the management team as well. "This is a very frustrating situation, not only for the people, but also for us. We now had to deal not only with the project challenges but to keep people motivated without resources", said the Hardware Manager.

Being experienced in both hardware and software design was also highlighted as a very valuable skill in developers in order to facilitate common understanding and agreement, especially when difficult trade offs were to be decided. The management team recognized that there was little of this skill among the developers at the beginning. They noted, however, that the developers learned a lot about each other's job which later facilitated their communication in the advanced phases of the development process.

The lack of proper support from the chip supplier was a major concern for both hardware and software managers. They felt that this lack of support had a major impact on the project schedule. The Project Manager commented, "We found serious bugs on the chip and it took us some time to convince the supplier that the problem was on the chip."

3.3 Case Study Two

3.3.1 The Company

The second company designs, develops and builds communications networks that enable carriers, service providers and enterprises to deliver content, such as voice, data and multimedia, to consumers around the world. It is a multi-billion dollar corporation with worldwide operations.

3.3.2 The Project

The project for this case study was again a new hardware and software release for an asynchronous transfer mode (ATM) switch platform to provide enhanced newer applications.

In order to get a global view and understanding of the hardware and software coordination mechanisms in this company, interviews were requested with a hardware manager, a software manager and a project manager who had previously participated in the same project. However, the workload and management priorities at the time this case study was done did not accommodate having interviews with a management team that had previously worked together on a finished project. Instead, the management team available for this case was in the early development stages of a new project. The

information released here is based on the managers past experiences and their plans as to how the project would be managed.

Because the interviewed management team was just beginning their project, their observations and comments represent a more current application of HW-SW coordination mechanisms than the first case.

The project had been with the company's senior management for a few months when they came to see it as a major opportunity for gaining competitive advantage. The project started about a month before the case study interviews.

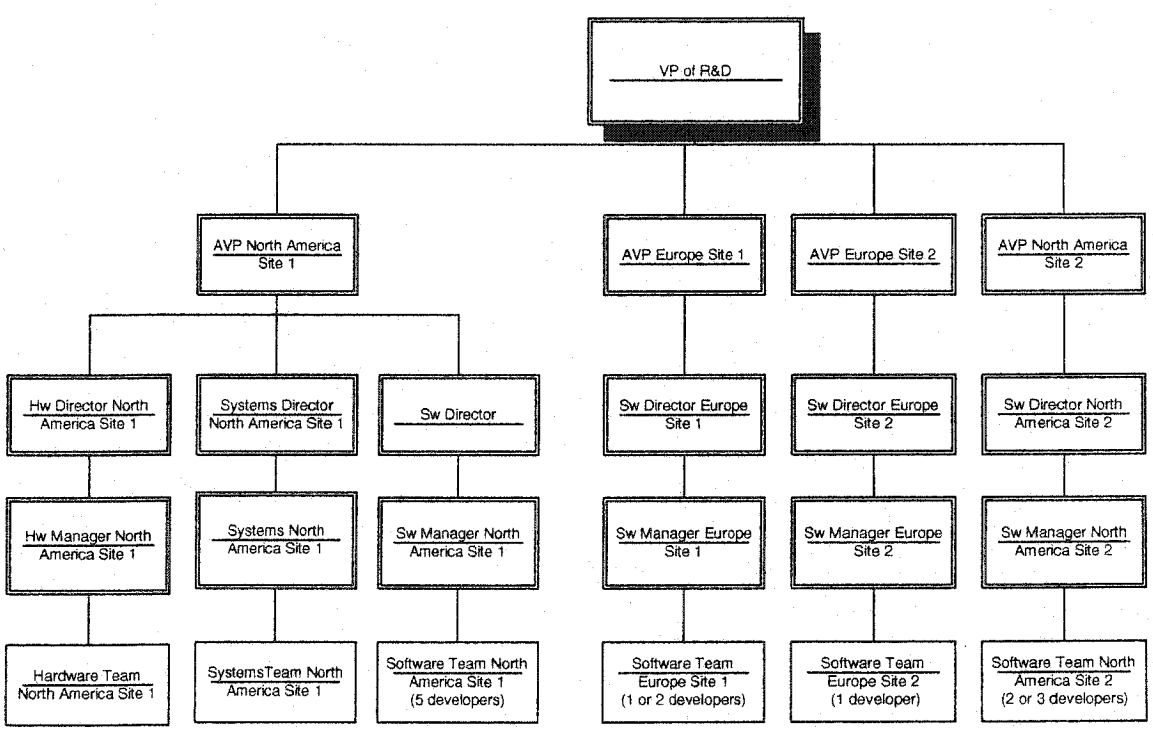
3.3.3 Time Line

The opportunity window for this project was tight so the schedule was a critical success factor for this project from the beginning. The project-planning phase started a few days before the end of November 2001. Although the ATM platform's product release date was not clear at that time, the project was expected to be finished by December 2002 in order to be able to converge with the platform's product release. In order to achieve the tight schedule, it was expected that the HW-SW integration phase last no more than one month.

3.3.4 HW-SW Organization

The organizational structure to support this project was multi-site with teams working in this product division all over the world. At its height, the software development team would have developers working on this project at two sites in North America and two sites in Europe. At least the Ottawa software team had been selected and consisted of five developers. Each site would be responsible for specific software features with a software manager at each site to trace milestones for that site's progress. Diagram 3 sketches the organization being put in place at the time of the interviews:

Diagram 3: HW-SW Organization Structure in Company Number Two



The hardware team was to be a single-site team working in the Ottawa office. It was to consist of five people including the hardware manager, two senior developers, one intermediate developer and one junior developer. A highly experienced Project Management team was to work heavily on this project to facilitate communication and information interchange between managers.

Along with the hardware and software groups, the system's group was to work jointly in the hardware and software development process. This group would be responsible for creating the project's functional specifications and assure that all information shared in the document database was understandable by both the hardware and software groups. They would also be responsible for all coordination needed upfront between groups before the integration phase.

There would be no software developers with previous background working in the other's discipline. In fact, the Software Manager maintained that he did not much need this type of expertise from the members of his team. On the other hand, there were to be two hardware developers with previous software development experience. The Hardware Manager commented, "In a strategic project like this with such a tight schedule, the multidiscipline experience is vital; even critical."

3.3.5 HW-SW Coordination in Review

The company set up web-based tools to communicate among team members. E-mail communication was expected to be one of the principal channels of communication for this project. Communication would occur in three different layers. The first communication layer was to be from developer to developer; however this type of communication was not expected to happen more than 10% of the time. In the second communication layer, the Project Manager would work with the different functional managers in weekly meetings to discuss project issues. In fact, the Project Manager was expected to spend as much as 70% of his time in these meetings. In the third layer, communication would flow hierarchically, from developers to functional managers to functional directors, and if necessary it could reach the VP of R&D (the common level of report).

As a means to promote communication and involvement amongst the designers from the beginning of the project development process, senior developers were involved in the project planning. Managers heard their opinions and tried to obtain a consensus. They focused on issues that represented a higher dispersion of opinions and discussed them further.

Another communication mechanism would be anchored on document reviews. As the project progressed, reviews would be carried out on the documents produced. When

relevant, this review would involve the other functional organizations in order to assure that the information in the document is not misinterpreted.

The reward system within the company is pretty well established. Each individual has a yearly evaluation to determine his/her performance. Although team rewards have been common in previous projects, the company's cost policies at the time of the case study had eliminated these rewards.

Hardware and software developers would use no shared designing tools. Any shared information was to be communicated through the channels outlined above.

3.3.6 Managerial Concerns Around HW-SW Coordination

A major concern from the software management perspective was the multi-site coordination mechanism: "A major challenge in this project is not to step on each other's toes; to not be working at different sites on the same document at the same time; and to not create pockets of expertise," commented the Software Manager.

Mutual misinterpretation between groups about shared documentation was a major concern in order to avoid delays and keeping with the schedule. Significant importance was to be given to document reviews and informal face-to-face communication. Unfortunately this type of communication would be limited between sites. However, it was to be promoted between groups at the same site.

3.4 Case Studies Lessons Learned and their Influence on the Thesis

In general, with the exception of company number two's Software Manager, all interviewees agreed that having both hardware and software design experience was seen as a critical success factor in product development. This was highlighted by the Project Manager of company number one: "...There's no doubt in my mind that having either hardware developers or software developers with both hardware and software experience is very useful...at least you should have one within the team..."

There was also evidence that shared documentation and agreement in the early stages of the product development process would strongly impact design cycle goals. As agreement between documents grows stronger during later stages of a project, the possibility of having a document misunderstanding and a related delay decreases.

Informal communication plays an important role in reaching an agreement. According to the interviewees, this ad hoc, hallway communication allows developers to understand and "appreciate" each other's job. This type of communication also encourages the groups to act as a single team.

Physical distance between developers can become a strong hindrance in creating a sense of unity. As the Software Manager of company number one stated: "Co-location is tremendously important in achieving project success."

Team rewards have been found not only as a means to motivate people but also as another source of team interaction and information interchange. According to the interviewees, team rewards are commonly given in the form of a team lunch or a team event. This "off the record" communication between team members helps them to get to know each other in a more personal way and to strengthen any relationships already established.

Company number one's organizational structure was simpler, with fewer levels to common report, in comparison to the organizational structure of company number two. According to what was discussed in the interviews, it seemed that the organizational structure in company number one facilitated the resolution of all conflicts that arose in the development process better than that of company number two, thereby allowing the HW-SW management teams of company number one to make important decisions more efficiently at each hierarchical level.

The above evidence on how the mechanisms proposed by the literature review were present in the case studies allowed the author to have a better understanding of their implications in the product development process of complex electronic systems and motivated a deeper research on the topic.

4. Previous Findings on HW-SW Coordination

The research done by Koch (1997) presented an opportunity to use her raw data and explore further results through new data gathering. The limited literature about HW-SW coordination in product development motivated the author to further research this subject. In the following section a summary on Koch's research is presented.

Koch (1997) investigated HW-SW coordination from a managerial versus technical perspective. As part of her research she conducted interviews with industry experts and then performed a case study. The case study took Koch to a more in-depth understanding of how hardware and software developers worked with each other according to the coordination mechanisms that were already in place. She concluded that differences between hardware and software developers could make it difficult for project managers to coordinate the two design functions during product design.

Koch (1997) suggested that the coordination of hardware and software components of a complex electronic system is difficult for two main reasons: both the design processes for hardware and software components and the educational and work experience of hardware and software developers are different; the personal skills and traits of hardware and software developers are also quite different. She concluded that such differences could lead to increased conflict and negative outcomes.

She identified six relevant coordination mechanisms for analysis in her study:

1. Number of levels to common report
2. Rotation
3. Co-location
4. Group-based evaluations
5. Extent of shared design documents
6. Extent of shared design tools

Koch (1997) concluded that "number of levels to common report" were negatively correlated with project success; this correlation, however, was found to be significant only for project cost goals. She also found that physical distance was negatively correlated with project success. Again, this finding proved only significant for cost goal success. It was found that "hardware and software design experience " and project success had a significant and negative relationship, the opposite direction of that predicted. "Extent of shared design tools" and project success were also found to have a significant and negative relationship, opposite of that predicted. She concluded that organization level initiatives (number of level to common report and physical distance) facilitate coordination.

On the other hand, initiatives to manage interdependencies (having both hardware and software design experience and shared tools) impede project success. These interesting but less significant results, surprised even Koch due to the fact that strong supporting evidence for a positive impact on project success was found in the literature, her

interviews and her case study. She even suggested that future research in the topic should use only one questionnaire for all respondents and pursue the effect that 'hardware and software design experience' has on project success.

5. Additional Findings About HW-SW Coordination

The suggestions provided by Koch (1997) in her recommendations for future research, the availability of her raw data and the accessibility to contacts in local telecommunications companies involved in complex electronic design, contributed to the author's decision that it would be worthwhile to pursue further research in this topic. The contradictory conclusions provided by Koch lead the author to a field investigation to verify whether or not her hypotheses and her conclusions were in the correct direction. This field investigation also pursued further information on how the positive conclusions of her research might influence other domains of project success. The case studies helped in building a theoretical framework to get a deeper understanding of how the proposed mechanism worked in practice; given that the results reported in her study strongly disagreed with the comments of some of the managers interviewed.

This study investigated further correlations on the hypotheses proposed by Koch (1997) using her raw data. Her data was condensed to a single respondent for each project. The resulting data was put together with a new set of 28 projects gathered as part of this thesis to provide a larger sample.

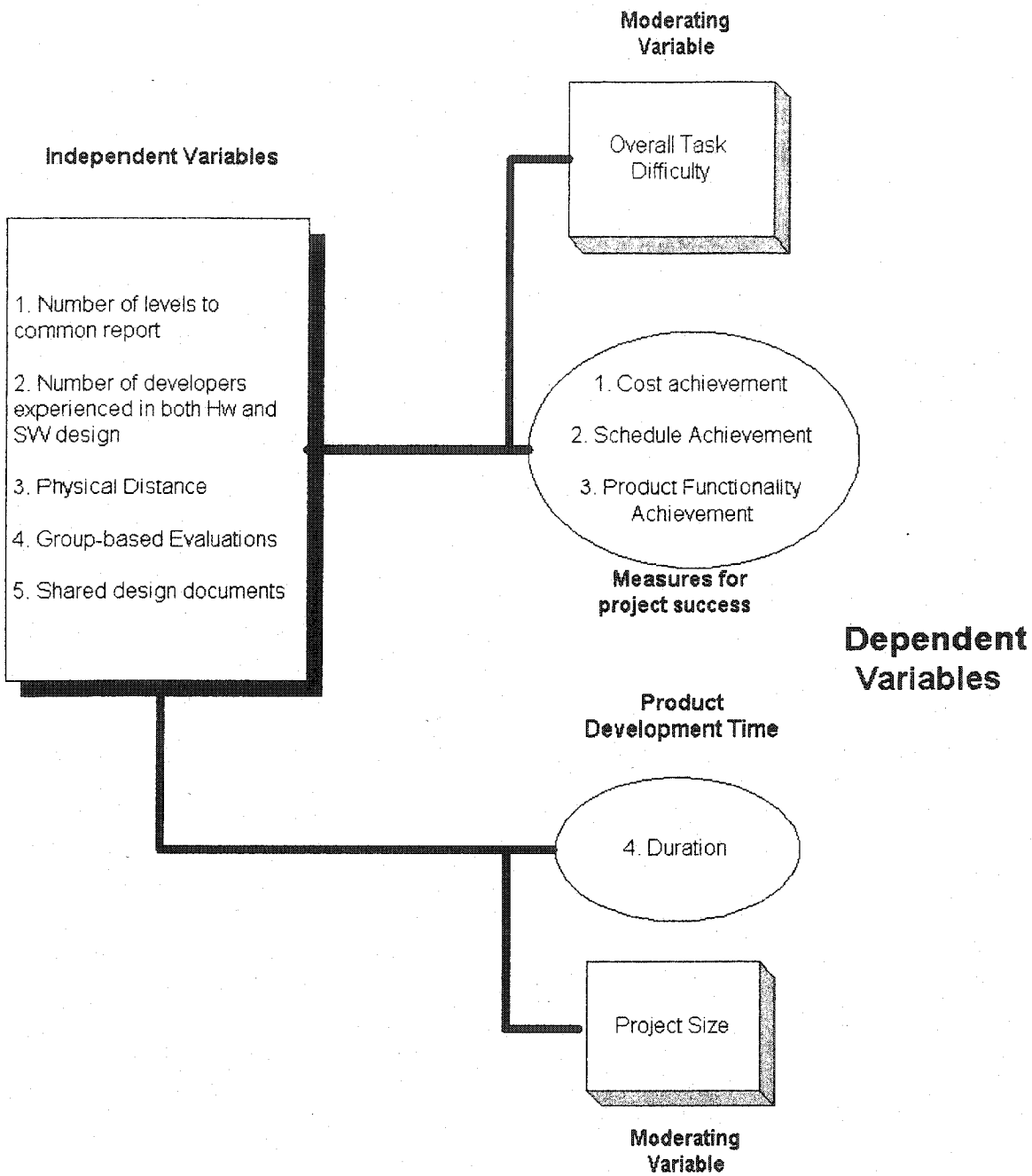
This chapter explains the theoretical framework used to generate hypotheses around proposed coordination mechanisms along with the new data gathering process.

5.1 The Model

The unit of examination used in the research was a completed project. Diagram 4 summarizes the expected relationships between the dependent and independent variables in the theoretical model. This model is adapted from Koch (1997). It includes the relationships hypothesized by Koch between the five independent variables (number of levels to common report, number of developers with both hardware and software development experience, physical distance, group based evaluations, and shared design documents) and three success measures (cost achievement, schedule achievement and product functionality achievement), all moderated by task difficulty.

The model also incorporates new hypotheses concerning the five independent variables and development project duration, moderated by project size. This part of the model was adapted from the research of Callahan and Moretton (2001) on the determinants of project duration.

Diagram 4: Research Model



Adapted from Koch (1997)

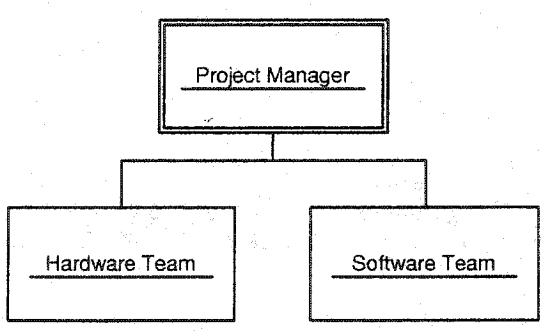
5.2 Hypotheses

The independent variables in Diagram 4 are applicable to the environment in which HW-SW development in complex electronic system design takes place. These coordination mechanisms were found to be consistent with the Koch (1997) study, my updated literature review and the two new field case studies. Based on this consistency, the following hypotheses are proposed:

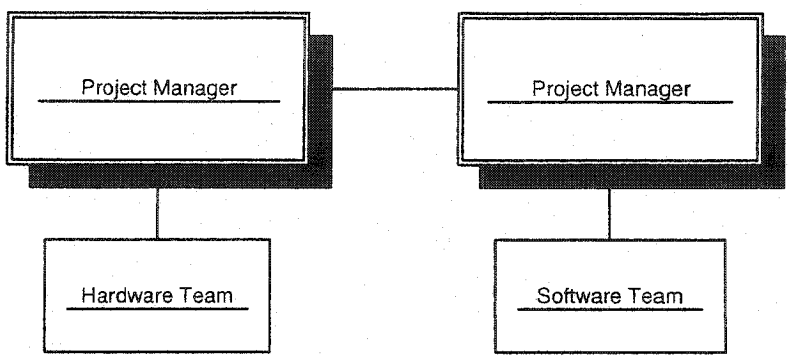
Hypothesis 1: The number of levels to common report is negatively related to project success.

The organizational structure of a development team might vary depending on the project complexity and company size. Because this variation may represent an endless set of organizational diagrams, four different diagrams were proposed and managers were asked to choose the diagram most representative of their organizational structure.

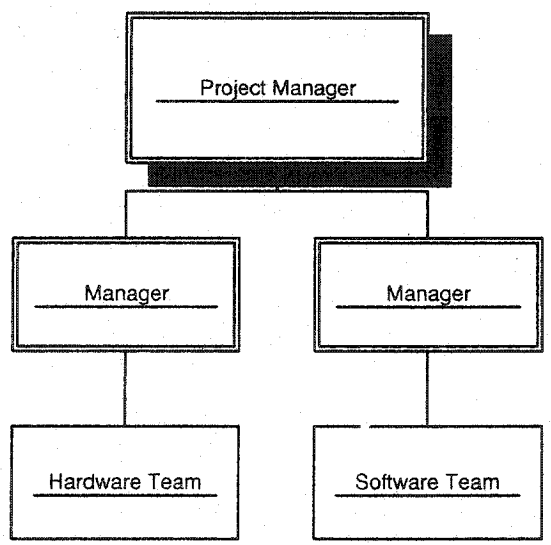
Here is how these diagrams looked in the questionnaire:



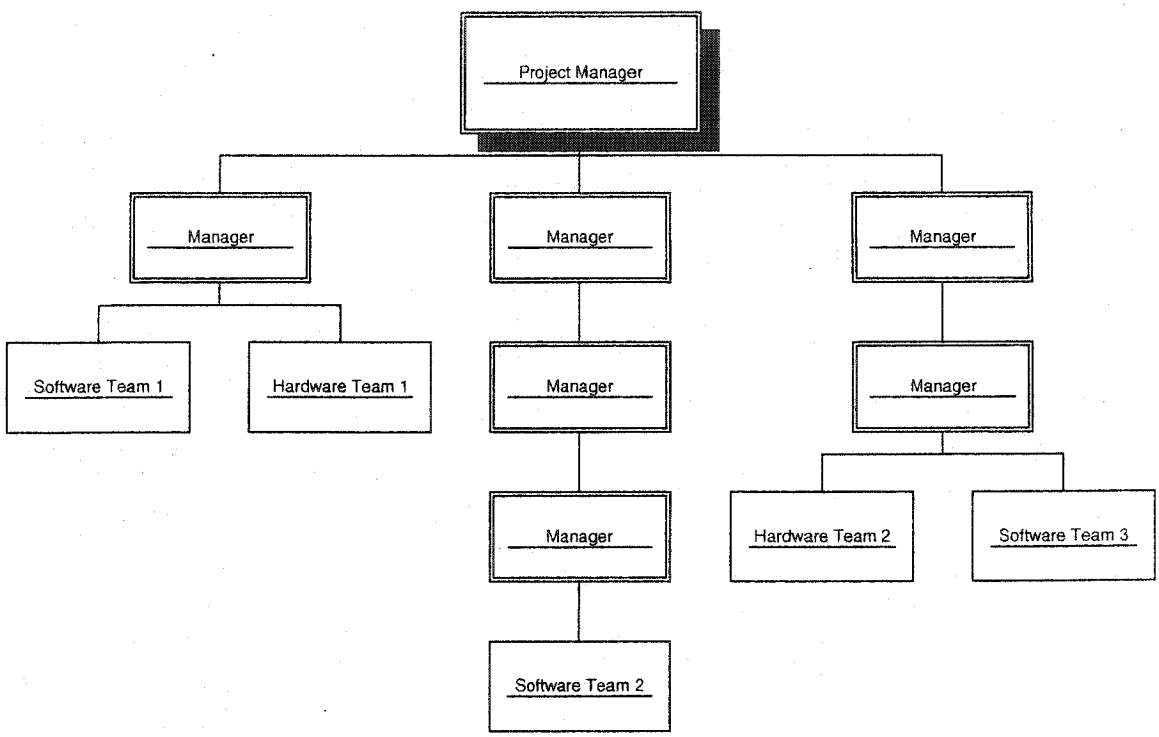
In the organization above has the lowest number of levels to common report when one single manager leads both hardware and software groups as if they were a single team.



This last structure, as the previous one, has only one level to common report; however, two managers at the same level are responsible for each functional team.



The above structure might be the most popular organizational structure within the R&D environment. In this structure there are two levels to common report: the functional managers and the project manager.



This last organizational structure is a more complicated one where several managers find their level to common report high up in the organization. This structure is popular in bigger R&D organizations where multiple sites, sometimes in different cities or countries, participate in a single project. This kind of organization was found in company number two as explained in the Case Studies section.

Hypothesis 2: The number of developers within a system development group that are experienced in both hardware and software design is positively related to project success.

Conflict resolution and reaching a common understanding between groups is easier when there are team members with a HW-SW perspective, having both hardware and software design expertise. This hypothesis was supported by the comments of five of the six managers interviewed in the case studies.

Hypothesis 3: Physical distance between HW-SW groups is negatively related to project success.

Physical distance arose as a significant concern in the case study with company number two. With mergers and acquisitions, companies often have several R&D groups running at different locations. When R&D groups work on a common project while separated geographically, coordination becomes a very challenging task.

Hypothesis 4: Group-based evaluations are positively related to project success.

Teamwork has become a highly valued skill by human resource recruiters when selecting designers. Motivation to work as part of a team should also include evaluation and rewards. Group-based evaluations measure the extent to which the R&D managers

evaluate hardware and software developers as a single team rather than evaluating developers individually or as independent teams.

Hypothesis 5: The shared used of design documents is positively related with project success.

Shared documentation was found in the case studies to be a significant means to coordinate and interface HW-SW development efforts. Shared project specification documents in early stages of the development cycle allowed hardware and software teams to keep a common focus on the functionality, the interfaces and constraints around which they developed. Further along in the development process cycle, updates to these documents and new documentation allowed them to track and anticipate any conflict at any given stage.

5.3 Moderating and control variables

An important consideration for a respondent when evaluating the realization of a project goal was the respondent's perception of the difficulty of the project and hence his or her perception of the ultimate success of the project. Project task difficulty is related to the degree to which project-costs are to be cut, schedule reduced and/or product functionality achieved.

For example, the perceived task difficulty of developing a navigation system for a publicly funded space agency could differ significantly from that of developing a telecomm switching system in a highly competitive market on different dimensions. Consider the difficulty of achieving the planned schedule and product functionality targets, for example. The short opportunity window afforded by a highly competitive market will demand a tight development schedule for the telecom switching system. In order to accomplish the schedule, the development team might take advantage of a previously developed platform and transfer it to this new product. On the other hand, the space navigation system might require extensive research and development of hardware and software components but on a more leisurely public sector schedule.

Callahan and Moretton (2001) used size as a control variable for the relationship between project duration and their project management independent variables. I followed the same approach.

5.3 Data Gathering Strategy

To obtain access to complex electronic system design companies, the author identified high-tech firms in the telecommunications, medical and aerospace industries through the following on-line guides:

1. The following web page is intended for business people working in and with Ottawa's technology sector. Its purpose is to help people and companies learn about each other and bring them closer. At this site, corporate information, management contacts and a general overview of each company are available.

http://www.ottawatechnology.com/

2. Similarly to the Ottawa's technology guide explained above, these following two sites provide information on Toronto and Alberta technology companies.

http://www.torontotechnologyguide.com/

http://www.albertatechnologyguide.com/

3. The following web page provides a brief description and information about the companies participating as expositors in Supercomm 2002. Supercomm is the premier annual communications and IT conference and exhibition held in Atlanta, Georgia each year. This web page provides access to a global marketplace of innovative products and services in the communications industry.

http://www.supercomm2002.com/productlocator/

The R&D directors, hardware and software vice presidents of companies participating in these guides were contacted by telephone and asked for the participation of a knowledgeable hardware, software or project manager within their organization. A confirmation e-mail describing the scope of the research, the profile of the project and company was sent. A sample of the letter sent can be found in Appendix 1.

When its willingness to participate was confirmed, the survey questionnaire was sent to the company via email. Both e-mail and telephone communication was used to follow up with the participating companies. A total of 92 questionnaires were sent out and 29 responses were received. One of those respondents did not match the management profile so it was left out from the study leaving a usable response ratio of: 28 / 92 = 30.43 %

5.4 A New Questionnaire-The Challenge

With the economic downturn in the high-tech sector, managers and developers in R&D organizations within companies have had a significant increase of workload and a significant decrease in resources. This made them very reluctant to invest time to answer the survey questionnaire. Although the survey promised to provide an executive report of the findings of the study, including results on how their firms and teams compared to the entire sample in return for their participation, many felt that taking more than 10 minutes to fill the survey out was not worth their time. In order to facilitate their response, a survey with a limited number of questions and few words per question but providing the required information was needed (Fink and Kosecoff 1998).

In order to be able to take advantage of the availability of Koch's (1997) raw data it was necessary to develop a new questionnaire that was easier to answer and analyze, but that provided congruent data in important areas.

Analyzing Koch's (1997) survey, several areas of the questionnaire were found to be unnecessary. There were results in Koch's work that showed little or no significance in important areas. The author identified areas in Koch's work that merited further investigation and pursued them.

The MS Word Form tool was found to be useful in developing the questionnaire. Tables, matrixes and menus were used along with boxes to mark the answers. The survey

consisted of three types of questions: multiple response, seven-point Likert scales, and short text answers. Few short text answer questions were included in order to reduce the time required to respond. A sample of the questionnaire is provided in Appendix 2.

5.5 Correlations on New Sample

The data gathered through the process described in Section 5.3 provided useful information to run correlation analyses in order to test the research model presented in Section 5.1 and to verify the relevant hypotheses. This section explains how the data gathered was coded, the correlation methods used and the results obtained for the new sample.

5.5.1 Data Set Coding

As mentioned in Section 5.1 project success was measured in four different domains:

1. Budget or cost achievement
2. Product functionality achievement
3. Schedule achievement
4. Product development time

Table 2 provides a summary on the coding scheme use for these dependent variables. Table 3 provides a description of the codes used for the independent variables, and Table 4 the description for the control variables "task difficulty" and "project size".

Appendices 2, 3 and 4 provide a detailed description on the relationship used to code the information gathered through the survey questionnaires as they were entered in the SPSS statistical analysis software package (Sweet 1999).

Table 2: Dependent Variables Coding

Question #	Var Name	Var Label	Definition
Nineteen a) and d)	ΔC	Cost achievement	Difference between cost goal achievement and cost goal importance for project success, from respondent's perspective
Nineteen b) and e)	ΔS	Schedule achievement	Difference between schedule goal success achievement and schedule goal difficulty from respondent's perspective
Nineteen c) and f)	ΔF	Functionality achievement	Difference between functionality goal achievement and functionality goal importance for project success, from respondent's perspective
Nineteen a), b) and c)	AvGA	Succgoal	Average of Q14cgoal, Q16sgoal, Q18fgoal (average goal achievement measure from respondent's perspective)
Thirteen	Duration	Q5months	Number of months that the project last from conception to full-scale production.

Table 3: Independent Variables Coding

Question #	Var Name	Var Label	Definition
Six	HW-SW exp	Pq7hsexp	Number of hardware and software developers on the project experienced in both hardware and software design.
Nine a)	# Levels	Q8levels	Number of levels to common report between hardware and software developers.
Eleven	# Cities	Q13city	Number of different cities in which hardware and/or software teams were located
Twelve	Freqcom	Hs7fcont	Measure of how often was informal communication used by both hardware and software teams.
Fourteen a)	Shareval	Pq17eval	Method of evaluating development teams
Sixteen	Docshar	Hs17d_sh	Measure of how often were design documents shared by both hardware and software teams .

Table 4: Controlling Variables Coding

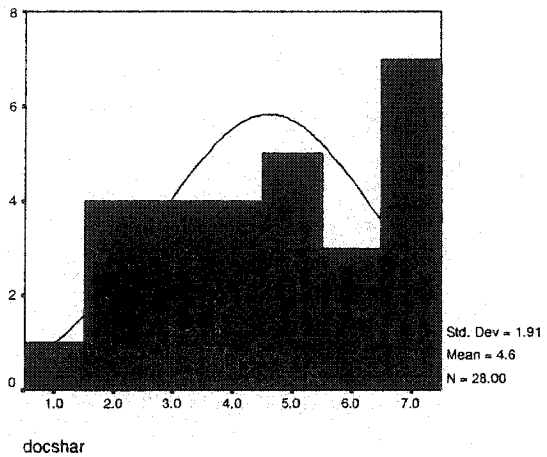
Question #	Var Name	Var Label	Definition
Eighteen	Tdifav	Taskdifctyav	Average perceived difficulty in achieving the cost, functionality and schedule goals on the project
Four and Five	Size	Size	Measure of how big the project was

5.5.2 Exploratory Data Analysis

Examining the new sample for outliers, missing values and data entry errors was imperative before doing any statistical analysis (Fowler 1993). An observation was considered as an outlier if it was so far removed from the other observations that it was taken to be an extreme value not representative of the sample. This assessment was important to identify unusual responses and determine the statistical distribution of each variable.

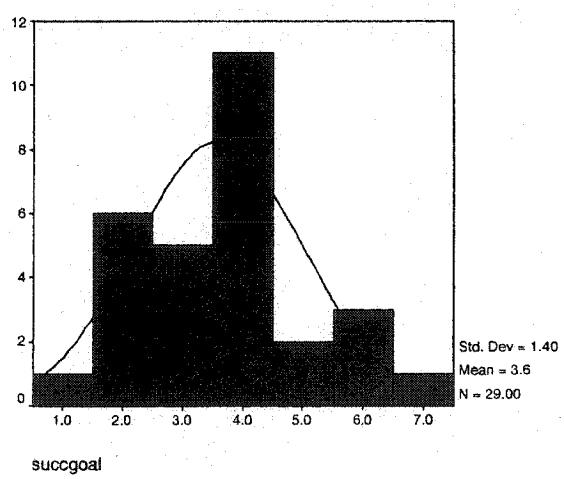
Graphical displays such as histograms and scatter plots were used to search for outliers within the sample. No outliers were found. Histograms were also used to assess the normal distribution of the variables. All independent variables were found to follow non-Normal distributions so Spearman's correlation tests were used in Section 5.5.3. Diagram 5 shows the non-Normal character of distribution for "extent of documents shared" variable.

Diagram 5: Histogram of "Extent of Documents Shared" Variable



On the other hand, the histograms for the dependent variables were closer to being Normally distributed. Diagram 6 shows an example of this distribution for the "AvGA" variable.

Diagram 6: Histogram of "AvGA" Variable



The descriptive statistics provided in Table 5 below gives more in depth information about each independent variable.

Table 5: Descriptive Statistics for the Independent Variables in the New Sample (n = 28)

Descriptive Statistics					
	N	Min.	Max.	Mean	Std. Deviation
# Levels	28	1.00	3.00	1.71	0.66
# Cities	27	1.00	4.00	1.33	0.73
Shareval	26	1.00	4.00	2.15	1.41
Freqcom	28	1.00	3.00	1.14	0.45
Docshar	28	1.00	7.00	4.60	1.91
HW-SW exp	22	1.00	40.00	7.5	8.77

Two respondents failed to answer the evaluation mechanisms for the HW and SW teams. As for the number of developers experienced in both HW-SW design the number of missing values was six.

5.5.3 Nonparametric Correlations

The following table presents a summary on the results obtained when running nonparametric Spearman correlations for the new sample.

Table 6: Correlation Results for the New Sample (n = 28)

Independent variable	Dependent Variable	Correlation coefficient
HW-SW exp	ΔC	0.33*
HW-SW exp	ΔF	0.32*
Docshar	ΔF	0.52***
Shareval	AvGA	0.33**
Docshar	AvGA	0.26*

*p < 0.1; ** p<0.05; ***p<0.01

The variable used to measure the presence of experienced developers in both HW-SW design within the team was the total number of such developers that participated on the project (HW-SW exp). As Table 6 shows, when this variable was correlated against the success measure variables, it showed statistical significance with (ΔC) and (ΔF). Variable Docshar was used to measure how often shared documents were used by both hardware and software teams. When running Spearman correlations between this variable and the success measure variables significant correlations emerged for ΔF and AvGA.

Group-based evaluations between HW and SW teams were measured with variable Shareval. When Spearman correlations were run between this variable and the success measure variables, significant correlations were found with the AvGA variable.

5.5.4 Correlations Controlling for Task Difficulty

Partial correlations between the dependent and the independent variables were run to look for significant relationships when controlling for averaged task difficulty. Table 7 presents the results for the new sample data.

Table 7: Partial Correlation Results for the New Sample (n = 28)

Independent variable	Dependent Variable	Correlation coefficient
Shareval	ΔF	0.41**
Docshar	ΔF	0.53***
Docshar	AvGA	0.28*

*p < 0.1; ** p<0.05; ***p<0.01

Table 7 shows how task difficulty moderates project success for the measure of how often design documents were shared by HW and SW teams (Shareval) when correlated with ΔF and AvGA measures. It also shows a moderating effect for the relationship between Shareval variable and ΔF .

5.5.5 Correlations of Independent Variables vs Product Development Time in the New Sample

Once the above coordination mechanisms were found to be significantly correlated to the first three project success measures as explained in Sections 5.5.3 and 5.5.4, their effect on reducing product development time was tested using Spearman correlation.

Product development time or "Duration" (Q5months) was measured as the number of months a project took from conception to full-scale production. The following significant correlations were found:

Table 8: Correlation Results for Independent Variables vs Duration in the New Sample (n = 28)

Independent variable	Dependent Variable	Correlation Coefficient
# Levels	Duration	0.36**
Freqcom	Duration	-0.40**
# Cities	Duration	0.38**
Docshar	Duration	-0.24*

*p < 0.1; ** p<0.05; ***p<0.01

5.6 Regressions for New Sample

Stepwise regression analysis was used to develop predictor models for the project success measures as a function of the independent variables. Tables 9 and 10 show the results.

When running stepwise regressions for the first three project success measures, ΔF showed a significant prediction model. It was found that the measure of how often design documents were shared by HW and SW teams, the use of shared evaluations and the number of different cities in which HW and SW teams were located significantly affected product functionality.

When running stepwise regressions for the duration variable, frequency of informal communication was found to significantly affect product development time.

Table 9: Regressions for Dependent Variables in the New Sample (n = 28)

Dependent Variable	Adjusted R^2[a]	F (sig)[b]	constant	Tdifav	# Cities	Freqcom	# HW-SW Exp.	# Levels	Docshar	Shareval
1. ΔC	0.10	3.92*	1.65	-1.98	-0.99	0.16	1.04	-0.08	0.29	0.41
2. ΔF	0.62	11.83***	-0.79	-4.01***	-1.92*	0.59	0.19	-0.88	4.17***	2.88***
3. ΔS	0.15	5.86**	2.60**	-2.42**	-1.16	0.54	0.46	-0.50	1.13	0.72
4. AvGA	0.07	3.08*	3.42***	-1.76*	-1.27	0.10	1.00	-0.59	1.43	1.32

Table 10: Regressions for Product Development Time in the New Sample

Dependent Variable	Adjusted R^2	F (sig)	constant	Size	# Cities	Freqcom	# HW-SW Exp.	# Levels	Docshar	Shareval
1. Duration	0.07	3.09*	5.25***	0.90	0.76	-1.76*	-0.25	1.39	-0.86	-0.53

*p < 0.1; ** p<0.05; ***p<0.01

[a] The R^2 value is an indicator of how well the model fits the data (e.g., an R^2 close to 1.0 indicates that we have accounted for almost all of the variability with the variables specified in the model). R^2 is adjusted for the degrees of freedom in the model.

[b] The F statistic is a standard overall measure of linearity of the model. A large value of F is preferred.

6. An Aggregate Sample

Once the new sample was tested, an aggregate sample was built by merging Koch's (1997) sample with the new sample. Appendix 4 shows the correspondence between the new survey questionnaire and the Koch's (1997) survey questionnaire along with the variable coding schemes used.

Since the Koch survey design included three different questionnaires directed to three types of respondents, the information provided by the three respondents was condensed to be able to match it with the single-respondent questionnaire of the new sample.

As an example, consider the case of project "Duration." Koch (1997) asked HW and SW developers as well as the project manager to estimate project duration. In a number of cases, these estimates were different for the same project. For the purpose of this current research only the Project Manager's (PM) response was used in the aggregate sample.

Detailed analysis of the information included in each type of questionnaire was carried out and through the use of correspondence rules (either by averaging or taking PM response) the relevant questions were matched in order to have a single measure for each variable in the Koch (1997) sample.

6.1 Variables

The data coding for the dependent variables described in Section 5.5.1 is consistent with that of Koch's (1997) data and hence is used straightforwardly in the aggregate sample.

Calculation of the independent variables of the aggregate sample followed the principles described in Section 5.1.1. Once a single respondent set was achieved, further calculations were performed to build a similar set of variables as described in Table 3 Section 5.5.1. Table 11 below illustrates the independent variables used in the aggregate sample.

Table 11: Independent Variables in Aggregate Sample

Var Name	Var Label	Definition
# Levels	Q8levels	Number of levels to common report between hardware and software developers.
Shareval	Pq17eval	Method of evaluating design teams
Cities	Q13city	Number of different cities in which hardware and/or software teams were located
Freqcom	Hs7fcont	Measure of how often was informal communication used by both hardware and software teams.
Docshar	Hs17d_sh	Measure of how often design documents were shared by both hardware and software teams.
HW-SW exp	Pq7hsexp	Number of hardware and software developers on project experienced in both hardware and software design.

6.2 The Aggregate Sample

Once a single respondent set was built for the aggregate sample, further analysis of this sample was needed. First the variable means of the two samples were compared. Second, similar analysis as that described in Section 5.5.2 was carried out.

6.2.1 Previous Sample vs New Sample

Before any analysis with the aggregate sample was performed, the two samples were compared. Table 12 and 13 compare variable means between the two samples. Using analysis of variance, no significant differences between these variable means were found.

Table 12: Comparison of Means of Projects Between Samples

		N	Mean	Std. Deviation	Min.	Max.
Duration of project (months)	**Koch Sample**	20	22.85	13.85	10.00	72.00
	New Sample	28	19.54	10.68	2.00	48.00
Project Cost (ln)	**Koch Sample**	20	14.12	1.32	10.04	16.12
	New Sample	16	14.33	1.66	11.16	16.52

Project cost (measured in U.S. dollars) was positively skewed, so the natural logarithm (ln) of this variable's value was used in the analysis.

Table 13: Comparison of Means of Independent Variables Between Samples

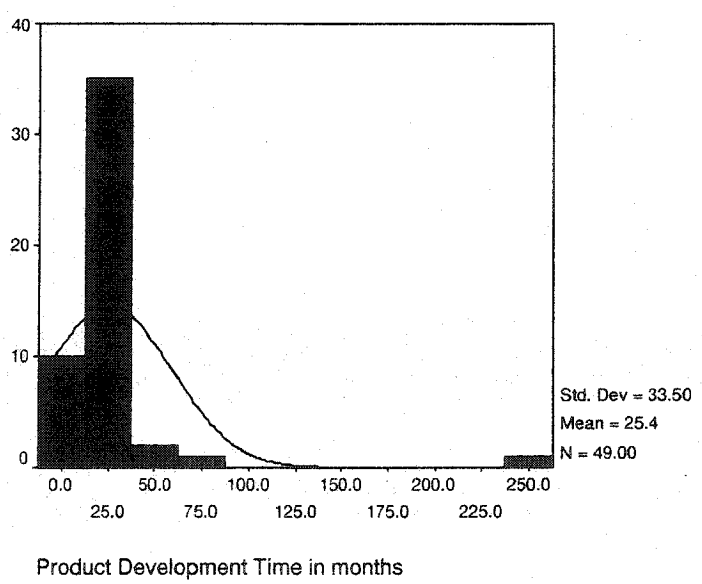
		N	Mean	Std. Deviation	Min.	Max.
# Levels	**Koch Sample**	20	1.65	0.74	1.00	3.00
	New Sample	28	1.71	0.66	1.00	3.00
Freqcom	**Koch Sample**	20	1.35	0.49	1.00	2.00
	New Sample	27	1.33	0.73	1.00	4.00
Shareval	**Koch Sample**	19	1.68	1.11	1.00	4.00
	New Sample	26	2.15	1.41	1.00	4.00
Docshar	**Koch Sample**	19	4.32	1.17	2.30	6.00
	New Sample	28	4.61	1.91	1.00	7.00

6.3 Aggregate Sample Exploratory Analysis

Again, examination of the sample for outliers, missing values and data entry errors was imperative before doing any statistical analysis. This evaluation was important to identify any unusual responses and to determine the statistical distribution of each variable. Frequencies, histograms and scatter plots were used for this purpose.

When displaying the histogram for the "Duration" variable one outlier in the Koch (1997) sample was found. An outlier was considered as an observation so far removed from the cluster of other observations that was taken as an extreme value not representative from the sample. Diagram 7 shows the histogram for this variable:

Diagram 7: Histogram of "Duration" Variable



The project that took 240 months to complete was removed from the Koch's (1997) sample. The number of projects in the resulting aggregate sample was 48. Histograms were used to assess the Normality of the variables. All independent variables were found to follow a non-Normal distribution. As in Section 5.5.2, the dependent variables were found to have a distribution very close to Normal.

After removing the outlier, the independent variables were checked for missing values. Table 14 shows the descriptive statistics of the independent variables.

Table 14: Descriptive Statistics for the Independent Variables in the Aggregate Sample

Descriptive Statistics					
	N	**Mean**	**Std. Deviation**	**Min.**	**Max.**
# Levels	48	1.69	0.69	1.00	3.00
# Cities	47	1.34	0.64	1.00	4.00
Shareval	45	1.96	1.30	1.00	4.00
Freqcom	48	1.54	0.79	1.00	4.00
Docshar	47	4.49	1.64	1.00	7.00
HW-SW exp	42	5.19	6.93	.00	40.00

Table 14 shows that different variables presented missing values. "HW-SW exp" presented the least amount of valid cases with 42.

6.4 Aggregate Sample Statistical Analysis

6.4.1 Non parametric Correlations of the Aggregate Sample

Table 15 below summarizes the significant correlation findings for the aggregate sample. It also shows the results found for the same correlations in the new sample reported in Section 5.5.3.

HW-SW exp appears to have a statistically significant correlation with the cost goal measure, just as it was the case in the new sample.

When the Freqcom variable was correlated with the schedule goal measure of project success it turned out to be statistically significant. This relationship was not significantly reported in the new sample analysis.

The Docshar variable showed significant results with the functionality, schedule and average goal achievement measures. These relationships were also significantly reported in the new sample data analysis.

Table 15: Correlation Results for the Aggregate Sample

Independent variable	Dependent Variable	Correlation Coefficient: Aggregate Sample (n = 48)	Correlation Coefficient: New Sample (n = 28)
HW-SW exp	ΔC	0.25*	0.33*
Freqcom	ΔS	0.28*	0.008
Docshar	ΔS	0.29**	0.22
HW-SW exp	ΔF	0.07	0.32*
Docshar	ΔF	0.49***	0.52***
Shareval	AvGA	0.15	0.33**
Docshar	AvGA	0.27**	0.26*

*p < 0.1; ** p<0.05; ***p<0.01

6.4.2 Correlations Controlling for Task Difficulty

Partial correlations between the dependent and the independent variables were calculated to look for significant relationships when controlling for task difficulty. Table 16 presents the results for the aggregate sample compared to the new sample.

Table 16: Partial Correlation Results for the Aggregate Sample

Independent variable	Dependent Variable	Correlation Coefficient Aggregate Sample (n = 48)	Correlation Coefficient New Sample (n=28)
# Levels	ΔC	-0.19*	-0.02
Docshar	ΔS	0.24**	0.22
Shareval	ΔF	0.28**	0.41**
Docshar	ΔF	0.52***	0.53***
Docshar	AvGA	0.31**	0.28*

*p < 0.1; ** p<0.05; ***p<0.01

Table 16 above shows again how task difficulty moderates project success for the independent variables considered. Several results were found to be significant as in Table 7 Section 5.5.4. Specifically, the significant relationships between the functionality goal success measure and, Docshar as well as team-based evaluations between groups, were also reported to be significant. The significant and positive relationship between the AvGA measure and Docshar was also confirmed.

Although Table 7 in Section 5.5.4 did not show a significant relationship between the cost goal success measure and the number of levels to common report for the new sample, Table 16 reports a significant and negative relationship between these variables in the aggregate sample. Similarly the schedule goal success measure reported a significant and positive relationship with the extent of design documents shared by HW and SW developers in the aggregate sample.

6.4.3 Correlations of Independent Variables vs Product Development Time in the Aggregate Sample

When running correlations between project "Duration" and the independent variables, the following significant correlations were found:

Table 17: Correlations Results for Duration in the Aggregate Sample

Independent Variable	Dependent Variable	Correlation Coefficient Aggregate Sample (n = 48)	Correlation Coefficient New Sample (n = 28)
# Levels	Duration	0.21*	0.36**
# Cities	Duration	0.33**	0.38**
Freqcom	Duration	-0.17	-0.40**
Docshar	Duration	-0.03	-0.24*

*p < 0.1; ** p<0.05; ***p<0.01

6.4.4 Regressions for Aggregate Sample

Once again, stepwise regression analysis was used to develop predictive models for the project success measures as a function of the independent variables. Tables 18 and 19 show the results.

As in Table 9 of Section 5.6, in the stepwise regression analyses of the dependent variables (project success measures), functionality goal and AvGA showed to have significant prediction models, the former in a greater degree. It was found that task difficulty, how often design documents were shared by HW and SW significantly affected product functionality and averaged goal achievement measures. The use of shared evaluations significantly affected product functionality.

Based on the stepwise regressions analysis of the "Duration" variable, number of levels to common report and project size were found to significantly affect product development time.

Table 18: Regressions for Dependent Variables in Aggregate Sample (n = 48)

Dependent Variable	Adjusted R^2[a]	F (sig)[b]	constant	Tdifav	# Cities	Freqcom	# HW-SW Exp.	# Levels	Docshar	Shareval
1. ΔC	0.08	5.51**	1.55	-2.35**	-0.53	0.92	1.22	-1.30	0.91	0.18
2. ΔF	0.48	15.21***	0.82	-5.05***	-1.57	1.11	1.04	-0.41	3.42***	2.24**
3. ΔS	0.18	11.20***	2.95***	-3.35***	-1.01	0.34	0.67	-0.45	1.57	0.90
4. AvGA	0.14	4.93**	1.43	-2.57**	-1.52	0.57	0.36	-0.19	2.13**	0.64

Table 19: Regressions for Duration in Aggregate Sample (n = 48)

Dependent Variable	Adjusted R^2	F (sig)	constant	Size	# Cities	Freqcom	# HW-SW Exp	# Levels	Docshar	Shareval
1. Duration	0.12	4.18**	1.57	1.94*	0.92	-0.08	-0.40	2.24**	-0.59	-1.02

*p < 0.1; ** p<0.05; ***p<0.01

[a] The R^2 value is an indicator of how well the model fits the data (e.g., an R^2 close to 1.0 indicates that we have accounted for almost all of the variability with the variables specified in the model). R^2 is adjusted for the degrees of freedom in the model.

[b] The F statistic is a standard overall measure of linearity of the model. A large value of F is preferred.

7. Conclusions on HW-SW Coordination

The statistical analysis presented in Chapters 6 and 7 provided evidence to support the significant relationship between the proposed coordination mechanisms and project success. First, the new sample provided supporting evidence; then, some of this evidence was confirmed by the aggregate sample and additional and new conclusions were encountered.

7.1 Results for the New Sample

Table 6 in Section 5.5.3 shows the positive relationship between the independent variable Number of developers experienced in both HW-SW design and the cost and functionality goal measures when considering their importance in project success. Although this variable did not show a significant relationship for the schedule success measure or the averaged goal achievement measure, the hypothesis as to the number of developers within a system development group having experience in both HW and SW design is positively related to project success is sustainable for the cost and functionality measures of project success.

There was found strong and sustainable evidence to support Hypothesis 4 (Group-based evaluations are positively related to project success). Results in Table 6 in Section 5.5.3 shows the positive and statistically significant relationship between shared evaluations of HW and SW developers and the three combined measures of project success. When

controlling for task difficulty this variable showed to be positive and significantly related to the functionality goal measure. Shared evaluations of HW and SW developers also appeared as a significant explanatory factor for the functionality goal measure in the regression analysis in Table 9.

Results in Table 6 in Section 5.5.3 show positive and significant relationships between the shared documents variable and the functionality achievement measure of project success. It also presents a positive and significant relationship for the average goal achievement measures. When controlling for task difficulty, Table 7 of Section 5.5.4, gives supporting evidence of the above relationships and the moderating effect of task difficulty. This variable also appeared as a significant explanatory factor in the regression analysis in Table 9. Table 8 in Section 5.5.5 shows how shared documents positively affect product development time reduction. These give compelling evidence to sustain Hypothesis 5 (The shared used of design documents is positively related with project success).

It was proposed that the suggested coordination mechanism would have a significant effect in reducing product development time. Table 8 in Section 5.5.5 shows the results of the correlations between the coordination mechanism variables and project "Duration".

On the one hand, frequency of informal communication and the constant use of shared design documents showed a significant and negative relationship with "Duration." On the other hand, number of levels to common report and number of different cities in which

hardware and/or software teams were located showed a significant positive relationship with "Duration." This means that the first mentioned mechanisms contribute to reduce product development time while the second mechanisms tends to increase product development time. In table 10 frequency of informal communication also appeared as a significant explanatory factor for "Duration."

7.2 Results for the Aggregate Sample

Table 16 in Section 6.4.2 provides evidence of the negative relationship between number of levels to common report and the cost measure of project success. These provide some evidence to affirm that the number of levels to common report is negatively related to project success. Hypothesis 1 is sustained for project cost goals.

The results presented in Table 15 in Section 6.4.1 give some evidence in favor of Hypothesis 2, which states that the number of developers within a system development group that have both hardware and software design experience is positively related to project success. Again hypothesis 2 is sustainable for cost goal achievement.

The significant and positive relationships reported in Table 16 in Section 6.4.2 is sustaining evidence for functionality goal achievement in support of Hypothesis 4 (Group-based evaluations are positively related to project success). This variable also appeared as a significant explanatory factor in Table 18 in Section 6.4.4

As previously seen in Section 5.7, evidence of a statistically significant and positive relationship was also reported in Table 15 in Section 6.4.1 and Table 16 in Section 6.4.2, providing compelling argument to support Hypothesis 5 (The shared used of design documents is positively related with project success). This variable was also a significant explanatory factor for the functionality and average goal achievement measures in Table 18 in Section 6.4.4.

As mentioned in Section 5.7, it was proposed that the suggested coordination mechanism would have a significant effect in reducing product development time. Table 17 Section 6.4.3 reports the results of the correlations between the coordination mechanisms' variables and product development time. Again, number of levels to common report, and number of different cities in which hardware and/or software teams were located demonstrated a significant and positive relationship with project's "Duration". This means that the previously mentioned mechanisms contributed to increase product development time.

7.3 HW-SW Coordination Findings

The first hypothesis was that the number of levels to common report is negatively related to project success. The analysis of the new sample did not provide sustaining evidence to confirm this hypothesis. However, when it was put together with the previously gathered sample, the aggregate sample presented supporting results for the relationship between levels to common report and meeting cost goals. There is some support in the data for this hypothesis, particularly for projects in which a major priority is to achieve cost.

Hypothesis 2 stated that the number of developers within a system development group experienced in both hardware and software design is positively related to project success. In the new sample, strong supporting information was shown not just for the cost goal achievement measure, but also for the functionality goal achievement measure of project success. Meanwhile, a weakly significant relationship was reported in the aggregate sample for the cost goal achievement measure. In her conclusions, Koch (1997) reported a significant and negative relationship between the percentage of developers within a system development group experienced in both hardware and software design and the individual and combined measures of project success. From the mixed results mentioned above, it was not surprising that when the two samples were put together the aggregate data did not provide support for this hypothesis.

With respect to Hypothesis 3 (physical distance between groups is negatively related to project success) the new sample did not provide evidence to support this hypothesis.

However, the aggregate sample provided with some evidence to sustain it for the schedule goal achievement measure. Informal, ad hoc communication between HW and SW developers was found to be significantly related to this success measure.

Compelling evidence was found to support Hypothesis 4 (group-based evaluations are positively related to project success). In the new sample the variable used to measure the group-based evaluations was significantly related to the combined measures of project success and the sense of this relationship was in the expected direction. When "task difficulty" was used to control the relationship between this variable and the success measures in the new sample it showed to be significant and positively related to the functionality goal achievement measure. It was also a significant explanatory factor in the regression analysis for the new sample. When analyzing the aggregate sample, this variable also showed a significant relationship in the expected direction with the functionality goal achievement measure in the correlation controlling for "task difficulty". As in the new sample, group-based evaluations were also found to be a significant explanatory factor for the regression analysis of the aggregate sample.

The last hypothesis affirmed that the shared used of design documents is positively related with project success. In the new sample the variable used to measure the extent of shared design documents was significantly related to the functionality goal achievement measure of project success and the sense of this relationships was in the expected direction. When "task difficulty" was used to control the relationship between this variable and the success measures in the new sample it showed to be significant and

positively related to the functionality and averaged goal achievement measures. It was also a significant explanatory factor in the regression analysis for the new sample. When analyzing the aggregate sample, this variable also showed a significant relationship with the schedule, functionality and average goal achievement measures, all in the expected direction. As in the new sample, shared design documents were also found to be a significant explanatory factor for the regression analysis of the aggregate sample. These present sustainable evidence to corroborate Hypothesis 5.

7.4. Effects of HW-SW Coordination Mechanisms in Product Development Time

The product development literature provides countless approaches to achieve shorter cycles but few have addressed in depth the HW-SW coordination approach.
This section will summarize the advantages of using these mechanisms in favor of shorter product development cycles.

Levels to Common Report

When analyzing Tables 8 and 17 for the new and aggregate sample, the significant and positive relationship between the levels to common report and the duration of projects implies that the higher the number of levels the longer the project. Furthermore, in Table 19 this mechanism appeared to be a significant explanatory factor in the regression model for the duration variable.

Consequently, it is reasonable to conclude that with more levels to common report, important trade-offs and decisions in the product development process take more time to climb the hierarchical ladder, delaying the development schedule.

Physical Distance

Two different variables were used to measure physical distance between developers. Frequency of informal communication and number of cities in which HW and SW teams

were located were found to be significant and negatively related to project duration in the new sample. The aggregate sample reported just a similar relationship for the number of cities in which HW and SW teams were located variable. Frequent informal communication demonstrated to be a significant explanatory factor in the regression model for the duration variable in Table 10. In concordance with Rauscher and Smith (1995) these mechanisms are identified as instruments in reducing critical paths in the development process through close collaboration. Product development time could be reduced as a consequence.

8. Summary and Conclusions

The conclusions on HW-SW coordination presented in Chapter 7 provide important contributions to the R&D literature. This section will explain how these contributions provide new light on HW-SW coordination, how R&D managers can get advantage of this findings and which fields can be improved by further research.

8.1 Contributions of the Thesis

There are a number of similarities and differences between the results of this research and those of the investigation developed by Koch (1997). One of the similarities was the fact that physical distance between HW and SW developers has a negative impact in project success. Another similarity was that the number of levels to common report was found to have the same direction and context as that reported by Koch (1997), and as is stated in Section 7.2. The smaller the number of levels to common report the more likely is the project success. This mechanism was also found to be significant success factor for projects in which a mayor priority is to achieve cost. These findings are congruent with those suggested by Rauscher and Smith (1995).

As to the relation of the number of developers experienced in both HW and SW design with project success, the findings in this research have a different direction from those reported by Koch (1997). She reported that this mechanism showed to be significantly related to project success and in the **opposite** direction as predicted. When analyzing this

mechanism in the new sample it turned out to be significantly related to project success and in the **expected** direction. It is reasonable to suggest that when the existing sample and the new sample were put together the negative and positive effects would have cancelled each other, thus yielding weakly significant results in the aggregate sample.

The most striking finding in this thesis is that, as suggested by Rauscher and Smith (1995), the wide use of shared design documents as an interface to promote joint understanding and ownership of objectives was found to significantly increase the likelihood of project success, which is a most remarkable and outstanding difference with respect to Koch (1997). In the same context, ensuring mutual accountability between HW and SW developers through shared evaluations systems was found to be significantly related to project success. Koch (1997) concluded no significant results for these mechanisms.

As explained in Section 2.2 product development time has become a major success factor for today's organizations. The introduction of product development time as a success measure in this thesis supports this reality. It is important to outline that levels to common report and physical distance, used as coordination mechanisms between HW-SW developers, were found to have a positive impact when related to project's duration.

8.2 Recommendations for Managers

The field investigation described in Chapter 4 outlined some of the managerial concerns about HW-SW coordination. Informal communication, shared evaluations, physical distance and wide use of shared design documents were outstanding within the list. This research provided some answers to those concerns.

As mentioned in Section 8.1, frequent informal communication between HW-SW developers was found to have significant effect in project success. The convincing evidence of the wide use of shared design documents between HW-SW developers in project success is unquestionable. This research also contributed significant support in the use of grouped based evaluations and minimizing the number of levels to common report as a coordination mechanism between HW–SW developers in achieving project success.

Managers in charge of HW-SW design teams may want to keep developers working as close as possible. Also, close informal communication between HW-SW teams should be promoted even when co-location is not possible. These mechanisms showed to be related to shorter product development cycles. Managers with a view in shortening product development time could be confident of using these mechanisms to increase the likelihood of project success without a contrary effect in their development schedule.

At the organizational level, keeping the decision making process at the lowest level of authority could increase the likelihood of achieving the cost goals. It was also shown that

this mechanism had a strong relationship with shorter development cycles. Managers would like to keep the lowest number of levels to common report between developers.

Paying close attention to the communication interface through the wide use of shared design documents will allow managers to enhance their product functionality goal achievement and, in general, increase the likelihood of project success. This mechanism could, in some cases, help to reduce the development cycles as well.

Mutual accountability for the project outcome through shared evaluations between HW-SW teams was demonstrated to be a compelling coordination mechanism in achieving project success. Managers may like to keep an evaluation system that assures a joint ownership of responsibilities and promotes a single team vision between developers.

The environment of high task interdependency and complexity described in this thesis is not unique to HW-SW development in an organization. All the coordination success factors presented in this thesis were found to contribute to mutual HW-SW developers' adjustment as explained by Thompson (1967). Other departments and functional areas (like sales and engineering) may also have similar coordination problems. The coordination principles described in this thesis may also help to solve coordination in other functional areas.

8.3 Recommendations for Future Research

This research has established the close relationship between the proposed coordination mechanisms and project success. It also emphasized the effect these coordination mechanisms have in reducing product development time. Further research is suggested in the following arenas.

As outlined by Grinter, Perry and Herbsleb (1999) multi-site R&D has risen importantly in recent years. Case study number two described multi-site coordination as a managerial concern in the HW-SW coordination process. Although physical distance between developers was shown to negatively affect schedule goal achievement and total product development time, these effects might be overcome through the effective application of electronic communication tools. It is suggested to pursue the electronic communication tools capable of addressing this reality in today's high-tech development environment.

Taking the decision making process to the lowest level of authority between the HW-SW groups was found as a success factor. However, how to control and provide decision authority to HW and SW groups separately and then coordinate these groups is not clear. Extended research in this authority management issue is also suggested.

Group-based evaluations positively affected functionality goal achievement, but it is not clear how best to design these shared evaluations systems. For example, on what joint

deliverables should HW and SW groups be evaluated, or how often should this deliverables be evaluated. Further research in this topic is suggested.

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Appendix 1: Invitation Sent to Participating Companies

Is your organization involved in Complex Electronic System Design?

Are you using cutting-edge ASIC's as a key part of your Product?

Or

Is HW-SW development for your products significant and critical?

I am writing a Master's thesis for the Telecommunications Technology Management degree at Carleton University (more information at http://www.sce.carleton.ca/Graduate/Framemain_TTM.shtml). The thesis will examine managerial issues related to HW-SW development coordination. Part of my thesis research entails a questionnaire study, and I am looking for recognized individuals within Multinational high-tech organizations interested in participating. Companies already participating in this research include: **CISCO, ALCATEL, SIEMENS and MARCONI.**

The Survey

I would like to ask for your important participation in this research. The survey consists of a brief questionnaire, the questionnaire should not take more than 10 minutes to answer and is intended for project managers, hardware development managers and/or software managers.

Benefits of Participation

After I have conducted the proper statistical analysis, I will provide each participant organization with a summary of findings from their project as well as a report comparing them with others in the industry or across industries. All information regarding participants and his/her organization will be kept strictly confidential. The findings of this study will help project, hardware and software managers better coordinate hardware and software development during their product development process.

Willing to participate

If you are willing to participate or want to refer some other person for this purpose, I would appreciate a reply to this message. If you believe that your product development process does not match my target profile or that you do not want to participate, please state your comments on your reply and the survey will not be sent to you.
If you have any question or need further information about this research I will be very glad to receive your comments.

I thank for your support.

Sincerely,

Edgar Ochoa

Master's Candidate
Telecommunications Technology Management
Carleton University
Home (613) 526-4770
Cell. (613) 302-8211
outtel@yahoo.com
jorosete@chat.carleton.ca

Appendix 2: Questionnaire

Thank you very much for taking the time to answer this survey; it should not take you more than 15 minutes to complete. Please select a project completed within the last year (or that is close to its completion) where hardware and software were designed at the same time. Please click in the boxes _____ to type your answers, click the boxes ☐ to mark your answers and use the drop down menu arrows Drop down arrow -> where multiple choices are available; for the open questions or if specified please type your answer. For easier navigation, you can move to the next field with the TAB key in your keyboard.
Please send your response to: jorosete@chat.carleton.ca

Sincerely,

Edgar Ochoa
Master's Candidate, Carleton University

General Background Information
1.- Name of project specified for this survey : _____

2.- What is your name and current job title? _____

3.- From product conception to full-scale production, how long did this project take? Years_____ Months _____

4.- Approximately how much money did your organization invest in this project? USD **$0.00** or check ☐ if unknown

5.- Approximately how many hardware and software developers in your organization were involved on this project?

Hardware _____ Software _____

Hardware and software design experience
6.- From the developers specified in the previous question, how many developers had both hardware and software design experience?
Hardware developers with software experience _____ Software developers with hardware experience _____

check ☐ if unknown check ☐ if unknown

7.- Please mark with an "X" your answer for the next set:

	Not useful at all						Very useful
	1	2	3	4	5	6	7
Of the **hardware** developers who had both hardware and software design experience, how useful was this experience for the development of the project specified for this survey	☐	☐	☐	☐	☐	☐	☐
Of the **software** developers who had both product hardware and software design experience, how useful was this experience for the development of the project specified for this survey?	☐	☐	☐	☐	☐	☐	☐

8.- During what part of the product development process did these experience prove more useful in the project specified for this survey?

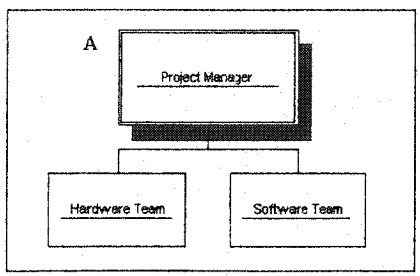
1.- High Level Design
2.- Low Level Design
3.- Project Hardware and Software Integration
4.- Testing
5.- Not Applicable
6.- Other Please specify

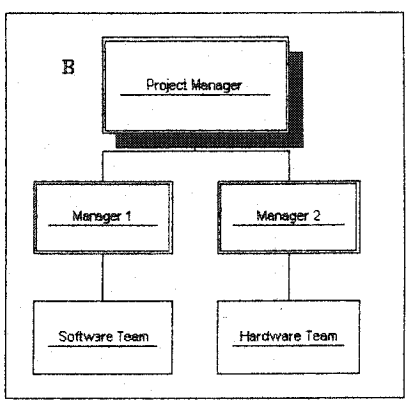
Please specify your answer in this box if option 6 was selected _____

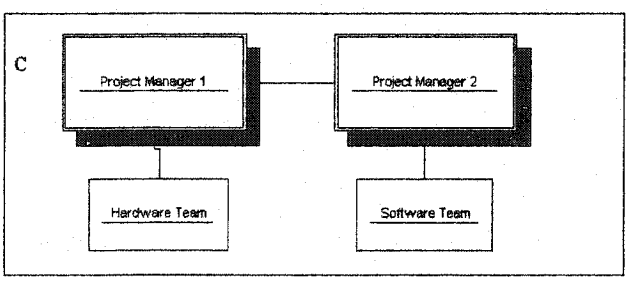
Number of levels to common report

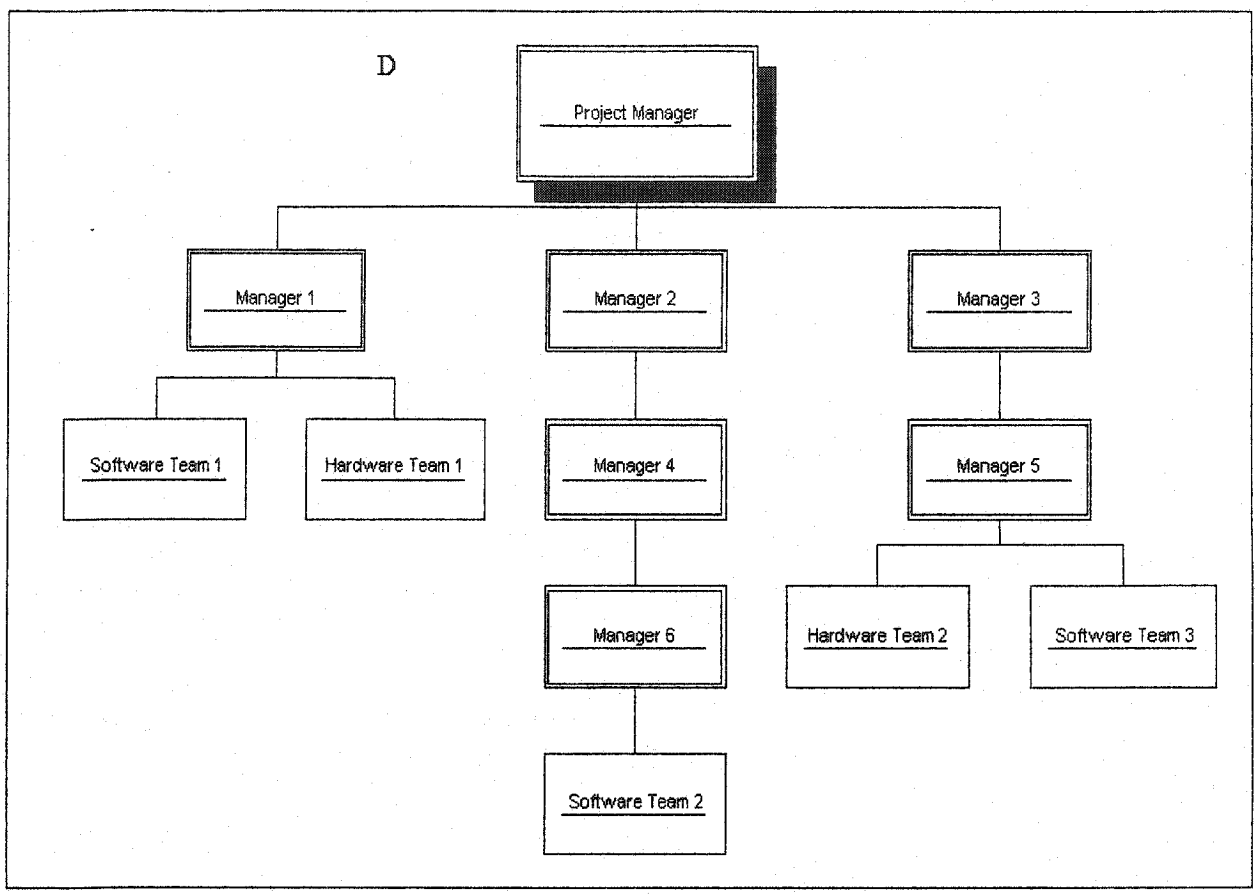
9. Here are four examples of what a system development group may look like. Please indicate which of the following diagrams represents the closest the system development group of the project that was selected for this survey, indicating which position you held.

Diagram _____ Position _____









Physical Distance

10.- How many hardware teams and how many software teams were there on the project specified for this survey?

Number of Hardware Teams _____ Number of Software Teams _____

11.- In case there were multiple teams assigned for this project in different locations, can you tell me where each hardware and/or software team (mark with an "X") was located, please specify city, province or state and country?

Teams				
Team #	Hw	Sw	City/State	Country
_____	☐	☐	_____	_____
_____	☐	☐	_____	_____
_____	☐	☐	_____	_____
_____	☐	☐	_____	_____
_____	☐	☐	_____	_____

12.- On average how often did the hardware and software development teams have informal communication (such as impromptu meetings in hallways) between each other during the project?

1.- At Least Once a Day
2.- Every Few Days
3.- Once a Week
4.- Two to Four Times per Month
5.- Less Than Once a Month

13.- For the teams located in the same city, how far were the hardware and software development teams located from each other ?

1.- Collocated Next to Each Other 2.- In The Same Floor
3.- In The Same Building 4.- In Another Building
Please specify your answer in this box if option 5 was selected

Group-based evaluations

14.- Please mark with an "X" your answer for the next set:

	Individuals	Hw and sw teams alone	Hw and sw teams combined	A combination of them (please specify)
When you made evaluations, did you evaluate.....	☐	☐	☐	____
When dealing with this project, did you reward.....	☐	☐	☐	____

Design Documents

15.- Please list the type of design documents shared by both hardware and software developers (for example, functional analysis documents, detailed specification) during the project specified for this survey and mark with an "X" in which part of the development process were they use.

DESIGN DOCUMENTS					
Part of the development process in which it was used					
Type of Document	High Level design	Low Level Design	Hw & Sw Integration	Testing	Other (specify)
____	☐	☐	☐	☐	____
____	☐	☐	☐	☐	____
____	☐	☐	☐	☐	____
____	☐	☐	☐	☐	____

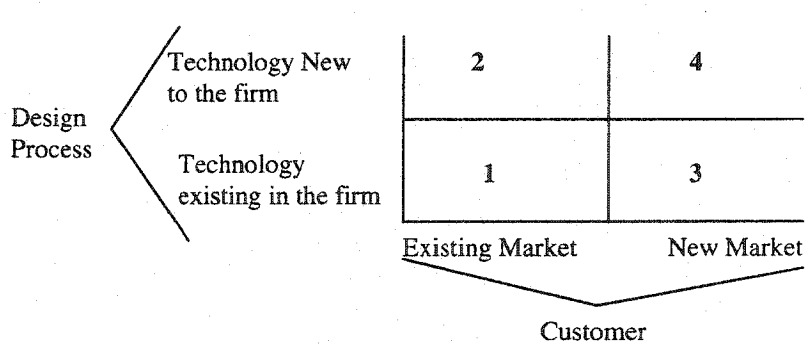
16.- How often did you use design documents shared by both hardware and software developers during the project specified for this survey?

1 ☐ Never 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ Every Day

Task Difficulty

17.- Can you please identify how the project for this survey fits into the following matrix (please write down the quadrant number)

Quadrant # 1



18.- Please mark with an "X" your answer for the next set:

	Strongly Disagree						Strongl y Agree
	1	2	3	4	5	6	7
"Initially, I felt that it would be very easy to meet the project's **cost goals** "	☐	☐	☐	☐	☐	☐	☐
"Initially, I felt that **the design cycle schedules** would be very easy to meet."	☐	☐	☐	☐	☐	☐	☐
"Initially, I felt that it would be very easy to meet all of **the product's functionality goals** "	☐	☐	☐	☐	☐	☐	☐

Project Success

19.- Please mark with an "X" your answer for the next set:

	Strongly Disagree						Strongly Agree
	1	2	3	4	5	6	7
"In the end, the **cost goals** were easily met."	☐	☐	☐	☐	☐	☐	☐
"In the end, **all of the design cycle schedules** were easily met."	☐	☐	☐	☐	☐	☐	☐
"In the end, **the product's functionality goals** were easily met"	☐	☐	☐	☐	☐	☐	☐
"The **cost goals** were crucial to the project's success"	☐	☐	☐	☐	☐	☐	☐
"**Meeting all of the design cycle schedules** was crucial to the project's success"	☐	☐	☐	☐	☐	☐	☐
"**The project's functionality goals** were crucial to the project's success"	☐	☐	☐	☐	☐	☐	☐
"I really enjoyed working on this project"	☐	☐	☐	☐	☐	☐	☐

20.- Was there any specific managerial initiative that proved to be successful to you in coordinating hardware and software developers in this project?

Appendix 3: Variables Calculation

Var Name	Var Label	Definition	Calculation
distchris	Hs8dist	Physical distance for researcher 1.	Respondent's answer, scale.
Co-location	Hs8new	Physical co-location distance between HW and SW teams.	Respondent's answer, scale.
docshar	Hs17d_sh	Measure of how often were design documents shared by both hardware and software teams .	Respondent's answer, seven point Likert scale.
cost	Pq3$	Project's cost	Respondent's answer.
#SWexp	Pq9#s	Number of software developers experienced in both hardware and software design.	Respondent's answer.
#HWexp	Pq8#h	Number of hardware developers experienced in with both hardware and software design.	Respondent's answer.
HW-SW exp	Pq7hsexp	Number of hardware and software developers on the project experienced in both hardware and software design.	pq8#h +pq9#s
HWdev	SW2#1st	# of hardware developers involved on the project.	Respondent's answer.
SWdev	HW2#1st	# of hardware developers involved on the project.	Respondent's answer.
HWSWexpr atio	Pq7perc	# of developers on project experienced in both hardware and software design to total numbers of developers.	Pq7hsexp / (HW2#1st+SW2#1 st)
Freqcom	Hs7fcont	Measure of how often informal communication was used by both hardware and software teams.	Respondent's answer.
# Levels	Q8levels	Number of levels to common report between hardware and software developers.	Respondent's answer.

Var Label	Var Name	Definition	Calculation
levelmgrs	Q8mgrs	Number of managers to common report between hardware and software developers.	Respondent's answer.
# Cities	Q13city	Number of different cities in which hardware and/or software teams were located	Respondent's answer.
shareval	Pq17eval	Method of evaluating design teams	Respondent's answer.
Q5months	Duration	Number of months that the project last from conception to full-scale production.	Respondent's answer.
Size	Size	Measure of how big the project was	(Pq3$) / (Hw2#1st+Sw2#1st)
costgoal	Q14cgoal	Cost goal success achievement from respondent's perspective	Respondent's answer.
schesgoal	Q16sgoal	Schedule goal success achievement from respondent's perspective	Respondent's answer.
fungoal	Q18fgoal	Functionality goal success achievement from respondent's perspective	Respondent's answer.
ctaskdifcty	Q11ctask	Response for cost goal achievement difficulty from respondent's perspective	Respondent's answer.
dtaskdifcty	Q12dtask	Response for schedule goal achievement difficulty from respondent's perspective	Respondent's answer.
ftaskdifcty	Q13ftask	Response for functionality goal achievement difficulty from respondent's perspective	Respondent's answer.
Cost achievement	ΔC	Difference between cost goal achievement and cost goal importance for project success, from respondent's perspective	q14cgoal - q15cimp

Var Label	Var Name	Definition	Calculation
Functionality achievement	ΔF	Difference between functionality goal achievement and functionality goal importance for project success, from respondent's perspective	q16dgoal - q17simp
Schedule achievement	ΔS	Difference between schedule goal success achievement and design goal difficulty from respondent's perspective	q18fgoal - q19fimp
succgoals	Success	Average of q14cgoal, q16dgoal, q18fgoal (overall project success measure from respondent's perspective)	(q14cgoal+q16dgoal +q18fgoal) / 3
taskdifctyav	Tdifav	Average perceived difficulty in achieving the cost, functionality and schedule goals on the project	(q11ctask+q12dtasK+q13ftask)/3

Appendix 4: Questionnaires' Correspondence

Var	Question#			
	New Sample's Questionnaire	Existing Sample's questionnaire		
		PM	HW	SW
Q1	2	1	1	1
Duration	3	6	7	7
Pq3$	4	10		
HW2#1st	5.1		9	
SW2#1st	5.2			9
Pq9#s	6.1	17		
Pq8#h	6.2	16		
Q8levels,	9 a)	11	12	12
Q8mgrs	9 b)	11	12	12
Pq10, HW7	10 a)	18	20	
Pq12, SW7	10 b)	20		20
Pq13city	11 d)	21		
Hs17d_sh	16		30	30
Hs7fcont	12		22	22
Hs8new	13			
Pq17eval	14.1	27		
Pq18rew	14.2	28		
Hs17d_sh	16		30	30
Q11ctask	18 a)	30	35	35
Q12stask	18 b)	31	36	36
Q13ftask	18 c)	32	37	37
Q14cgoal	19 a)	33	38	38
Q16sgoal	19 b)	35	40	40
Q18fgoal	19 c)	37	42	42
Q15cimp	19 d)	34	39	39
Q17dimp	19 e)	36	41	41
Q19fimp	19 f)	38	43	43
Q26enjoy	19 g)	45	50	50