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Survey of Concurrent Engineering Environments and the Application of Best Practices towards the Development of a Multiple Industry, Multiple Domain Environment

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Survey of Concurrent Engineering Environments and the Application of Best Practices towards the Development of a Multiple Industry, Multiple Domain Environment

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ABSTRACT

This thesis investigates the best practices of fifteen existing Concurrent Engineering Environments (CEE). A CEE is defined as any environment, from physical to virtual, designed to facilitate concurrent engineering with multiple domain experts real time. All existing environments surveyed have been focused on the aerospace industry showing significant reductions in design time and cost. I have identified hardware, software, and peopleware as three major classifications as well as sixteen subcategories with which to compare the different CEEs. The success in reducing time and cost of designs seen in the aerospace industry with the introduction of CEEs can and should be leveraged into additional domains and industries. This thesis explores the attributes of existing environments, the needs of additional industries, and the recommended concurrent engineering environment configuration appropriate for a multi-industry/multi-domain focus.

DEDICATION

I dedicate this thesis to my wonderful family and my extremely supportive wife whom I could not have done this without.

ACKNOWLEDGMENTS

Thank you to Dr. Joshua Summers who has consistently supported my research and allowed me to grow as an engineer.

Thank you to SCRA for providing partial funding for my masters education and the encouragement to complete my degree while working full time.

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CHAPTER ONE:

CONCURRENT ENGINEERING ENVIROMENTS

Decisions made during a product's design phase generally establish the majority of manufacturing costs and dictate the amount of production time required. In fact, the National Research Council has determined that nearly 70% of a product's cost is determined in the first 5% of the design process, shown in Figure 1 [1]. This is even more apparent in large system design and integration [2,3]. Generally, in large system design, initial meetings are held to discuss the design space or the design volume to which subsystems are held, constricting the design freedom available. For example, in a recent project, while designing a naval ship, the design volume assigned to the engine compartment was initially reduced to allow for payload stowage based on requirement estimates. Later this reduction was determined to be excessive for the design needs but it was too late to change since there was insufficient time to design a new power plant configuration and the cost of the engine room design would increase unnecessarily. To mitigate this issue, the right people must be brought together early in the design process to communicate, collaborate, and share expertise that drive these decisions.

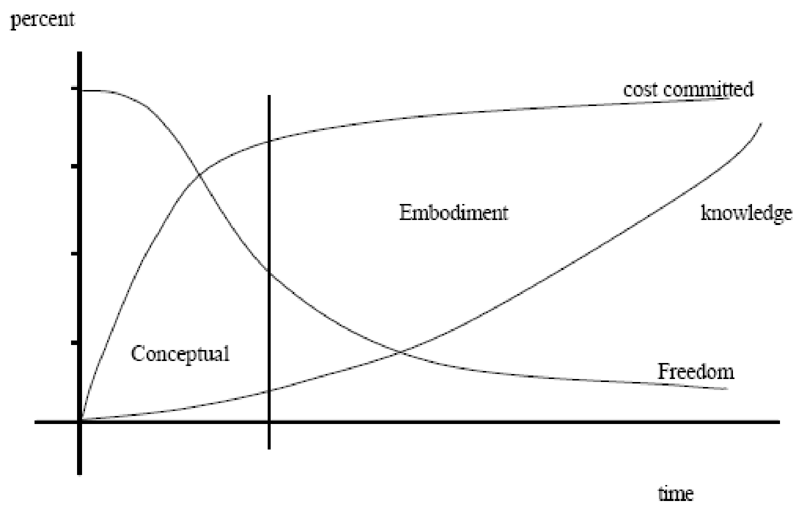


Figure 1: National Research Council Design Plot [1]

Figure 1 shows that decisions made early in the design stage have the greatest impact on the committed design cost. To improve these design decisions, it is important to add domain experts to a design team early to ensure key aspects are considered prior to losing design freedom [4]. Furthermore, as the design process progresses, design freedom is reduced. From this we can conclude that the best opportunities for integrating experts, as applied to cost and quality of design, occur early during the conceptualization phase of design and during design reviews stationed early in the process. This is the view of design proposed by the concurrent engineering community [5,6,7].

A tool used to facilitate design collaboration and concurrent engineering is a Concurrent Engineering Environment (CEE). Throughout this thesis a CEE is defined as any environment, from physical [5] to virtual [8], designed to facilitate concurrent engineering with multiple domain experts real time. Some results from implementation of a concurrent design facility at Jet Propulsion Laboratories have shown great reductions in cost, time to repair and an increase in the number of designs performed per year; see Figure 2 [9].

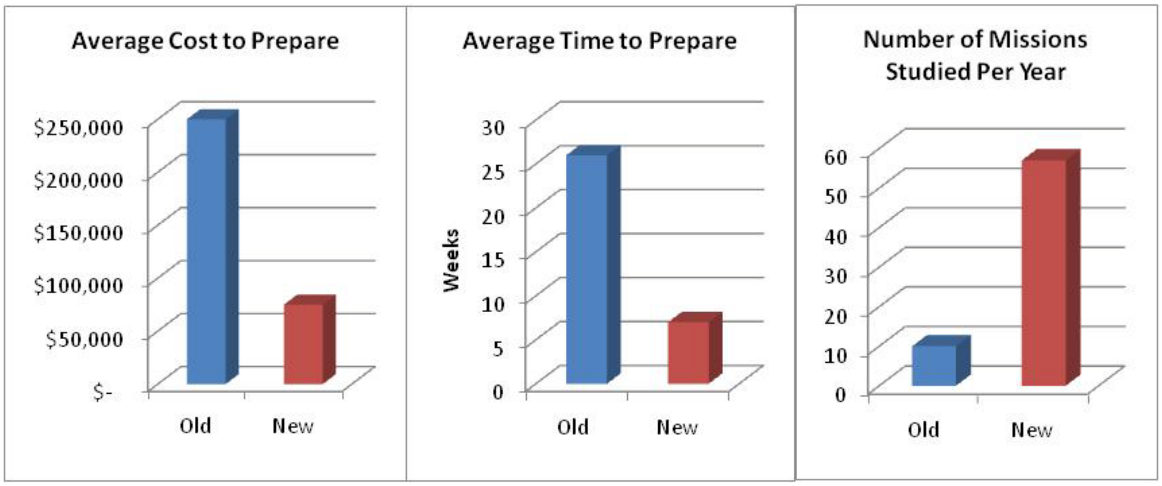


Figure 2: Concurrent Engineering Environments Benefits [9]

Uses of the Concurrent Engineering Environments

Concurrent engineering environments (Concurrent Design Environments, Concurrent Design Centers, Design Studios, Collaborative Design Environments, etc) can be used for multiple reasons such as development of proposals, conceptual design, design reviews, and other group decision meetings and activities. Through these activities, CEEs have been shown to reduce cost and time in the development process [9]. As design is an iterative process [10], these activities may reoccur throughout the development project, as seen in Figure 3 [11]. Each stage of the design, analysis of problem, conceptual design, embodiment of schemes, detailing and design reviews is a point at which a concurrent engineering environment could be used to support the various activities. However, most environments have been developed to support a targeted activity, rather than the broad range of potential applications. In addition to supporting high level design activities, the environments also facilitate the quick cycling of sub-activity iterations, such as through concept exploration where multiple variants can be considered concurrently with several design experts providing their input in real-time.

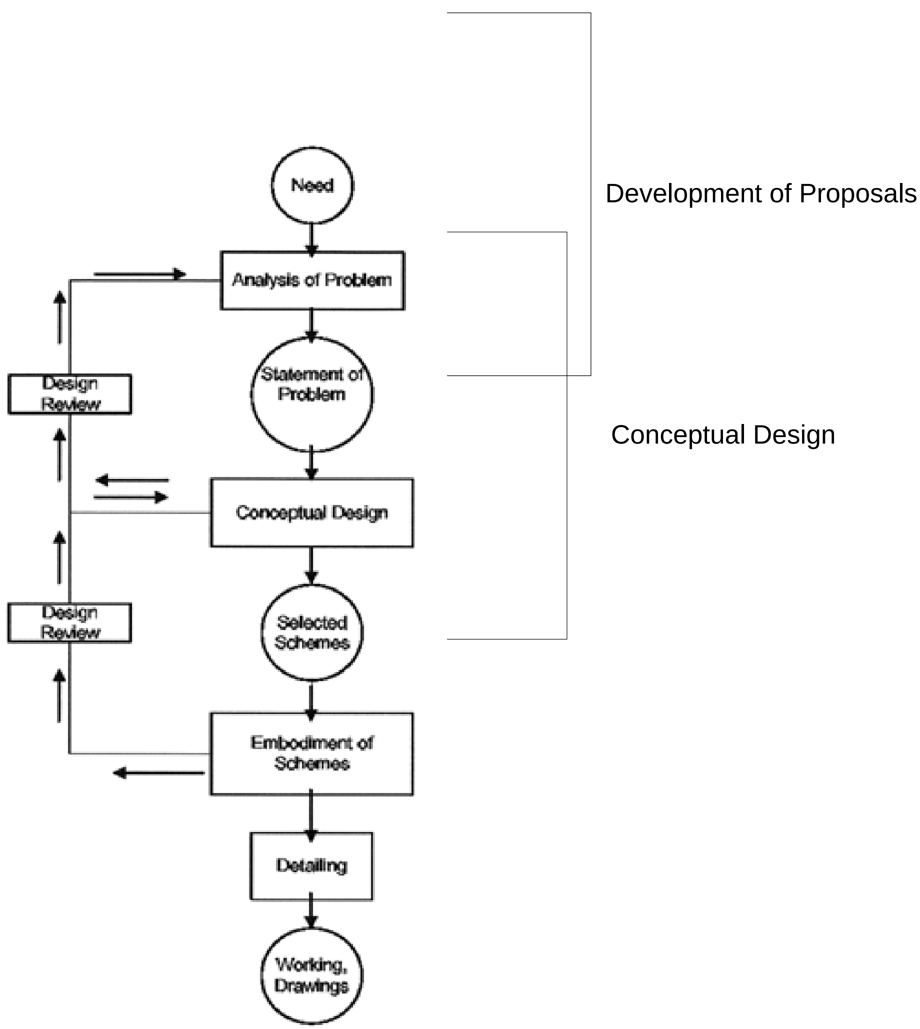


Figure 3: Design Process Model [11]

Proposal Development

After the NASA's Jet Propulsion Laboratory (JPL) had noted success with Team-X and the use of concurrent engineering environments to reduce the cost and time it took to develop a design, the issue of needing additional work to utilize their existing staff of engineers arose [9]. They then developed Team-1 which essentially uses the same concurrent engineering environment used for conceptual design to write proposals and grant requests. This is a defined and standing team of individuals that focus on proposal development, including contract personnel, technical writers, accountants, and program managers. Each newly supported subject matter expert also brought their own software requirements, such as image editing software for the technical communication specialists and accounting software for the financial specialists. The required software and peopleware were modified, yet the hardware was not changed. With these modifications to the teams, JPL has shown that the same facility could reduce the time and money required to perform other activities [9].

Conceptual Design

The conceptual design stage describes the formulation of design concepts based on problem/mission statements, constraints, and criteria. This stage is followed by the embodiment or detailed design phase as denoted by the vertical line in Figure 1 and is a key point in establishing the resultant cost and quality of a design [1].

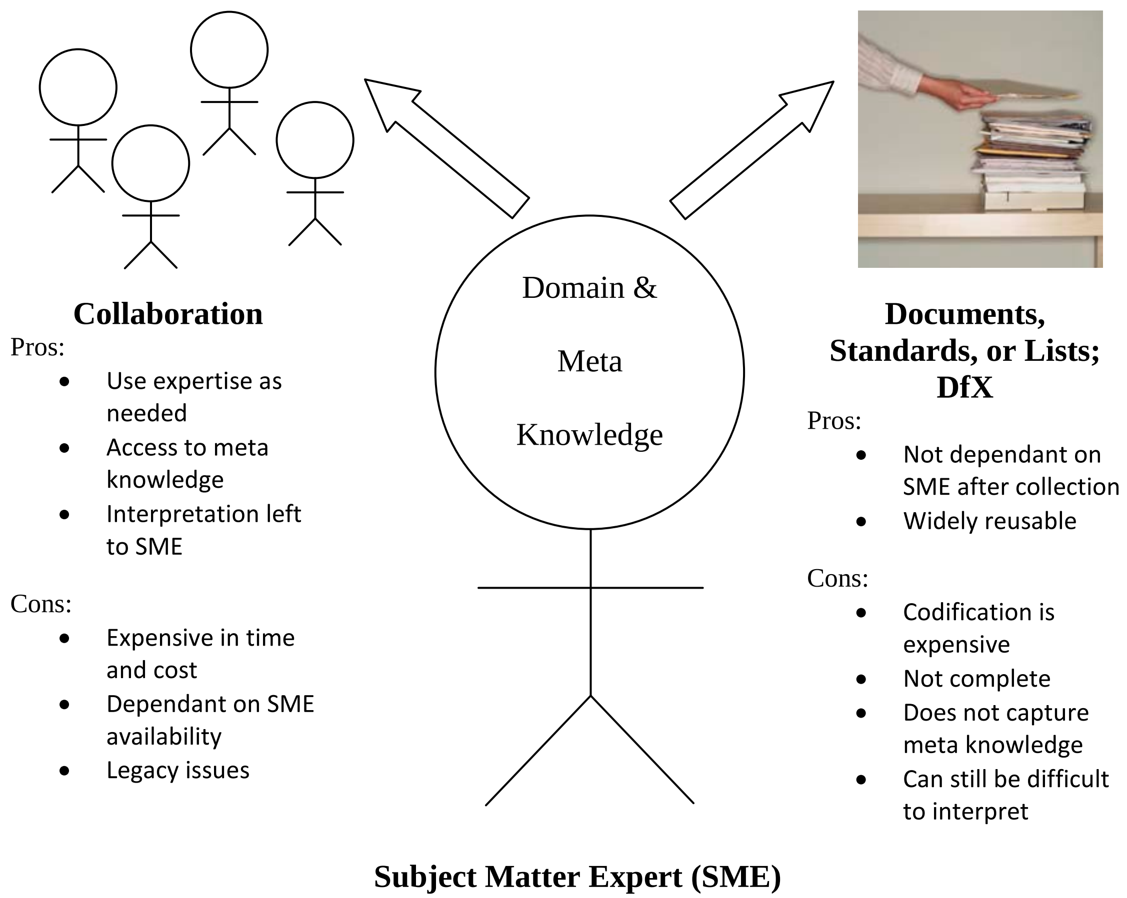
Design Reviews

A design review is a gathering of experts intended to select and evaluate a given solution [10]. The design reviews represent instances of interaction between agents working towards a common goal. Design reviews are commonly conducted to eliminate/reduce risk during the design process. Due to the required interaction between the team, customer, model, and design artifacts it is a perfect opportunity to facilitate the interchanges through the use of a concurrent engineering environment.

Concurrent Engineering Approaches

There are three fundamental levels of expert integration: the human-human level, the physical level, and the systems level. Typically, early development stages for the design of large, complex systems, such as an automobile, bridge, aircraft, naval ships, or spacecraft, require numerous person-hours, spanning several weeks in order to develop, explore, evaluate, and select concepts [12]. During this conceptualization phase, multiple iterations are performed sequentially usually in response to critical issues, adding time to the design phase and, thus, the cost [11]. Delays associated with critical issues are often compounded when other subsystems are not immediately informed of the changes resulting in futile effort on out-of-date concepts. Significant progress has been made in the tools and application of concurrent design which could aid in reducing the total design time and cost required to design any system [9].

There are two competing strategies for incorporating subject matter expertise knowledge of manufacturing and production earlier in the design process: design for manufacturing (assembly, welding, costing, etc.) and expert integration [13]. The first approach, design for X (DfX), has been explored extensively in the literature and in industry. Typically, this approach requires the capture of expertise the form of rules and guidelines as found in design manuals and design automation systems. While this has proven successful in reducing time to market and production costs, these successes are found in small scale products or specific localized areas of large products such as reducing the number of connectors or making assemblies self-aligning [14]. Large scale projects, such as ship design, are complex and prove difficult to capture all the manufacturing and production rules necessary [15]. Therefore, the second approach of integrating experts strategically in the design process is discussed further here within.



Thesis Research Questions

Based on the aforementioned issues, the research questions are:

- What software supports concurrent engineering? Software has become an integral part of design engineering. Software is used to collaborate, analyze, model, visualize, and integrate. By understanding what software can fill those necessary roles as well as integrate together effectively a successful concurrent design center can be constructed.

- What hardware supports concurrent engineering? Hardware is required to support individual designers, facilitate concurrent discussions of a team, integrate the design model, visualize a design, and possibly run domain specific experiments to gather data.

- What peopleware supports concurrent engineering? Although the software and hardware are vital components of a concurrent engineering environment, the processes and methodologies used to solve a design problem truly define the environment. Issues associated with design roles, conflict resolution, definition of the design process, to what degree is the design concurrent, and how teams are formed.

- How should a multidisciplinary/multi-industry concurrent engineering environment be designed? Other industries should be able to benefit from the success enjoyed by the aerospace industry's concurrent engineering environments. An environment can be established to be flexible enough to support multiple industries and multiple domains.

- How can information (e.g., intellectual property, classified data) be protected in teams composed of members from multiple organizations? This would benefit industries such as the automotive industry with second tier design agents and the government with classified data handling requirements for weapons platform design.

To answer these questions, a literature review of current operational practices was conducted to determine best practices. In reviewing the methodologies, software, hardware, and peopleware used by other entities it was important to keep the end requirements of a multi-industry facility, which would build on current practices and facilities. Concurrent engineering facilities that currently exist are focused on design projects in the aerospace industry. However, the benefits and advantages of these facilities can be leveraged across many other engineering disciplines and design applications including defense, automotive, and consumer products. Furthermore, the specific tools, guidelines, and procedures for concurrent engineering will vary with changes in the complexity, scope, and domain of the projects. Essentially, there is not an off the shelf product a large system integrator may purchase to integrate systems tools effectively. Additionally, the methodologies by which suppliers may integrate their results and designs into the systems level model without relinquishing their intellectual property rights need to be established. Thus, the lessons learned, best practices gleaned, and facilities developed to support aerospace mission design serve as a basis for realizing concurrent design facilities, guidelines and procedures for large scale manufacturing and design.

CHAPTER TWO:

CONCURRENT ENGINEERING SOFTWARE

In modern engineering, design software has taken an enormous role. Tools such as spreadsheets and word processors revolutionized private, government, and academic industries after their advent in the late 1970's. These tools are now commonplace and used to communicate business, financial, and technical information. There is numerous software required or desired to operate a successful concurrent engineering environment. They include software to facilitate collaboration, support analysis, support integration, perform modeling, and to support visualization. Further, these software packages can be commercial off the shelf (COTS) items, modified COTS, and custom in house software tools [16].

Software to Support Collaboration

Software for collaboration aids in the flow of information between team members, both remote and collocated. These tools include software to coordinate to exchange design information. These tools can be designed to be used remotely or by a collocated team either concurrently or intermittently.

Access to required information during collaborative design is a significant issue. In an effort to accommodate the designers schedule and need for information, databases can be used to pool information in an easily accessible and searchable format. For instance, the Space System Rapid Design Center at Ball Aerospace uses an internet vendor database that compiles costs and availability of vendor parts and products [8]. By storing this information ahead of time, the designers can focus on the product and not on who should be called externally to discuss availability of parts or their cost.

Another use of collaborative software tools is remote meetings between distributed personnel [17]. Personnel can be geographically distributed, distributed across organizations, time zones, or collocated. The use of this type of software allows for a leader to run a meeting in whichever manner they chose between agents almost anywhere in space and time.

Software to Support Analysis

Analysis is vital to modern engineering and is more accessible than it has been in years past. Multiple mathematical computation tools (Matlab[1], Mathmateca[2], Mathcad[3], and Simulink[4]), finite element analysis tools (IDEAS[5], NASTRAN[6]) and statistics packages (MS Excel[7], Crystal Ball[8]) are available from many different vendors. Designers can select these tools based on familiarity, availability in an organization, ease of use, or best function.

Software to Support Visualization

Visualization software is extensively used in engineering to bring thoughts, ideas, and sketches to a format that is transferable, integratable, and manufacturable. Numerous

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[1] www.mathworks.com
[2] www.wolfram.com/products/mathematica/index.html
[3] www.ptc.com/appserver/mkt/products/home.jsp?k=3901
[4] www.mathworks.com/products/simulink
[5] www.ideas-eng.com/finite_element.html
[6] www.mscsoftware.com
[7] office.microsoft.com/excel
[8] www.oracle.com/crystalball/index.html

computer aided design tools (CAD) are available to choose from (Solid Works[9], Solid Edge[10], Pro-E[11], CATIA[12]) and interchange formats exist, such as ".igs," to allow files in one format to be converted to another. By developing these drawings and solid models in virtual space it is possible to identify any interferences between subsystems, assembly issues, and other design questions without the expense of building a physical model of each artifact. These models can be incrementally updated as the design changes allow for the final set of drawings to be nearly complete at the end of the design of a system or set of systems.

Software to Support Integration

With the advent of distributed teams, large complex electronic design software tools have been developed to support the integration of multiple software tools and designers. Product Data Management (PDM) software is available to allow designers to "check-out" a model to work on it and subsequently "check-in" to then allow others access to the model. Products like PDXpert[13], features built in to Solid Works[14], and MS SharePoint[15] provide PDM functions for various data and documents.

Software to Support Modeling

System models can be generated using multiple software packages. Many concurrent engineering environments use linked MS Excel spread sheets to integrate the

[9] www.solidworks.com
[10] www.plm.automation.siemens.com/en_us/products/velocity/solidedge/index.shtml
[11] www.ptc.com/products/proengineer/
[12] www.3ds.com/products/catia/welcome/
[13] www.buyplm.com
[14] www.solidworks.com
[15] sharepoint.microsoft.com

subsystem designs into a system model [7,18], which captures weight, payload, thrust, cost, and all other attributes which define a design artcle. Custom programs have also been written in Matlab, Labview, and other programming languages. Specific design tools are also available depending on the design article. When endeavoring to design a small satellite, a software package called Small Satellite Tool Kit is available to integrate the model [19].

Levels of Customization of Software

There are numerous reasons for an organization to customize software tools for their specific use and reasons to not modify software. One reason to modify COTS software is to make use of efficiencies, if the design is very specific there are features a company can add to their Computer Aided Design (CAD) tool to automate the title block and drawing number/designation information to save time. The three levels of software customization: COTS or no customization, Modified COTS, and Custom Built Tools [20,16].

Commercial Off the Shelf (COTS)

COTS software tools affords an organization certain benefits. First this is the most time effcient category of software during setup. If the need for a tool is identified and a product exists to fit that need it is as easy as buying from a vendor. Additionally a support structure will more than likely already exist for that piece of software allowing for risk mitigation if issues should arise and training courses may be offered for the tool. This is an approach that is used by some concurrent engineering environments such as the

Concurrent Design Facility at Aerospace Corporation [18] to keep the cost of maintenance and training low.

Modified COTS

Modified COTS software implies that customized features have been added to a commercial package to fit the particular need of a facility. Some examples of customization can include document handling features such as automated title blocks, custom codes added to a finite element package, or custom costing methodologies added to existing price modeling software. This type of customization is appropriate when solving similar tasks numerous times. Rangel and Shah researched the application of DFM recognition customization in the commercial IDEAS package [21].

In-House Customized

When environments are tasked to solve highly specialized tasks using custom approaches and intellectual property, a completely new software tool, not relying on any COTS tools, would be required. These in-house products can be built up over time and provide an exemplar for future designs within an organization [22].

Summarize Software for Concurrent Engineering Environments

A host of different software is used in practice at concurrent engineering environments, both domain specific and domain independent. There is no one master list for software that must be used in a concurrent engineering environment but each of the major software categories including analysis, collaboration, integration, and modeling need to be addressed with either a COTS, modified COTS, or custom software solution.

When choosing software to fill these roles, they can be considered as independent decisions. For instance, a center could choose a custom integration tool and a COTS analysis tool. A visual representation of this notion can be seen in Figure 4.

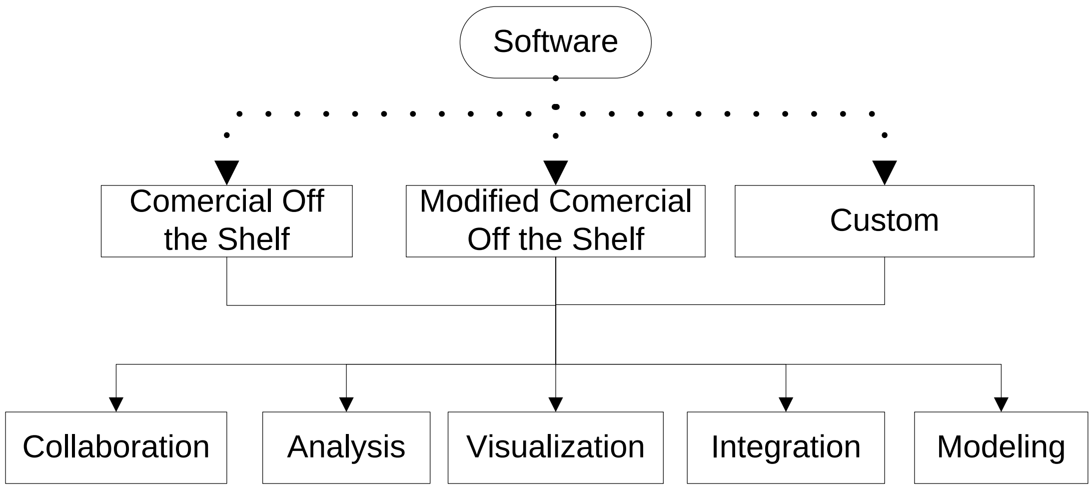

Figure 4: Software Decision Tree

The dotted lines represent an “and/or” decision meaning a center could use software that is COTS along with additional Modified COTS or Custom software, or any combination of the three categories. The solid line indicates an “and” decision indicating that software for collaboration, analysis, visualization, integration, and modeling must be included in the setup of a concurrent engineering environment.

CHAPTER THREE:

CONCURRENT ENGINEERING HARDWARE

Another key consideration in establishing a concurrent engineering environment is the electronic/computational hardware. The hardware serves many different functions within the environment including supporting the individual engineer/designer, servers to tie the individual hardware components together, visualization hardware, communication hardware, and individual domain specific pieces of hardware. All of these hardware items work in concert to support the concurrent engineering activities within the environment.

Individual Engineer Support Systems

In bringing experts together in a design space, hardware support is vital. Computers have revolutionized engineering processes in the last century and support all of the aforementioned software tools required for various engineering functions. Supplying individual support hardware capable of reliably operating all of the required tools is vital to a successful concurrent engineering design session, whether they be permanent, mobile preconfigured, or external mobile systems.

Permanent Desktop Systems

Permanent desktop systems have the benefit of constant integration into a concurrent engineering environment. The software tools can be loaded and tested ahead of time with little risk that settings will change rendering the system incompatible with the environment. Desktops are inherently more powerful and expandable than laptop technologies, resulting in a conceivably better user experience. The only disadvantage is that any additional non-standard required tools would need to be added prior to a session, requiring additional setup considerations [7,23,24]. Also, it is conceivable that a designer may not be familiar with the setup, for instance a MAC user being forced to use a PC system.

Mobile Preconfigured Systems

Mobile preconfigured systems may be preferred by larger companies with numerous employees. If each participant already has a mobile computer with the organization, they can be configured to interact with the concurrent engineering environment servers while still retaining the interface with which the participant is familiar or requires. One of the concerns with this approach is the chance of the system settings being modified offline so that it will not communicate correctly with the servers [25].

Support for External Mobile Systems

A location with common data connections such as network, video, audio, and others is commonly referred to as a kiosk. This approach is convenient with customers and external consultants when custom tools are required to participate effectively and IP retention is paramount. The interface the user is most familiar with is convenient but will take additional support to accommodate that wide of a range of settings [7,26].

Platform and Server Support

The individual support is important to give the designers access to the tools they need, however, the thrust of a concurrent engineering environments is to facilitate communication and interactive design. To that end servers are used to connect the individual computers, to give access to common tools and increased computational power, and to facilitate external communication whether it is Voice Over IP (VOIP) phones, video teleconferencing, or virtual meeting space. The three functions of a server are to store information, to enable data analysis, or to foster communication. These functions can be performed by separate servers or by the same server.

Information Server

Every center surveyed in industry uses a common information server to warehouse information, data, and the system model. Information from previous designs and solutions to common issues can be accessed quickly by anyone in the environment. When domain specific test hardware was used, the information server was used to store the resulting data for reference and incorporation into the design. Finally, in all cases, the common system model was stored on the server and the designer would either update the information on the server or the server would pull the information from their individual subsystem data sheets [7]. This connectivity is vital to linking together the designers and the design data.

Analysis/Modeling Server

Analysis and modeling servers are used widely in industry; some companies have built a business out of computational analysis availability. One example of an analysis server is the SUN Microsystems Mechanical Computer-Aided Engineering (MCAE) which is specifically designed for structural analysis. By dedicating and designing a server to support that one function, expiedent results can be achieved, which is important for an environment which wishes to reduce total design generation time [18].

External Gateway Server

Gateway servers are used for communication between servers and communication hardware. With the growing popularity of VOIP communication systems and video teleconferencing, the computation support requirements for communication has grown. A dedicated server insures that communication can be supported with adequate bandwidth, which, from personal experience, can be quite distracting while attempting to communicate virtually. Additionally, when multiple servers are used, a few for analysis, one for information, and one for communication, a gateway server would be used to integrate the servers and allow the servers to communicate with each other [18].

Visualization Hardware

Visualization hardware facilitates graphic communication. Fruchter discusses the importance of shared graphic modeling environments in interdisciplinary design with multiple perspectives [27]. Considering that multidisciplinary experts are required for concurrent engineering, a host of different perspectives will be used and visualization is vital to communication. Two types of support hardware can be used to support visualization hardware, that which displays and that which supports interactive graphic communication.

Group Displays

Group displays can be in multiple forms but they all serve the same function. Some examples of group displays available are projected screens, either rear or front, plasma, or liquid crystal displays. They all support group viewing and discussion of graphic information. By displaying the same graphic in front of multiple perspectives, unique views and creative solutions may be drawn out. Applications including virtual reality and immersion into designing have been researched as aids to engineering design. Group displays are meant to pull the users into the information graphically and are important tools for coordination in a concurrent engineering environment [28].

Interactive Displays

Interactive displays are similar to group displays with one key difference, they allow real time manipulation of the displayed artifact. With this added ability, the group can view, comment, discuss, and modify a graphic. This graphic can then be saved and disseminated to the group for individual use. There are a few available pieces of hardware that facilitate this function: smart boards, LCD sketch pads, and touch screen displays. The LCD sketch pads would require a group display as well as this interface [29]. An example of an interactive surface table from Microsoft can be seen in Figure 5. The multi-touch feature on this table makes it ideal for an interactive group meeting [30].

Figure 5: Microsoft Surface Table[16]

Communication Hardware

Communication hardware is an important consideration in concurrent engineering environments if certain functionalities are desired such as remote participation, recording of sessions for later review, and to ease discussions. Two types of communications capture are discussed further, audio and video systems.

Audio Systems

In a large facility with roughly 20 computers, a few displays, and other noisy pieces of electronics, it may be hard to make one designers voice heard by the entire

[16] http://www.guardian.co.uk/technology/blog/2007/may/30/microsoftsurfa

group [19]. A microphone system, either for the presenter or one for each participant can be used to facilitate verbal communication. This would also allow for the generation of an audio recording of a design session as well as integration with a web conference for remote participation.

Video Systems

The video systems used in concurrent engineering environments can be viewed as additive to an audio system. It makes little sense, other than for security purposes [7], to record or provide video of a session without coupling in audio. Individual webcams for each participant or for the entire group will allow for video recording of a session, video integration to remote participants, and facilitate communication by projecting an individual designer on a group display. [29]

Domain Specific Hardware On-Site

In some instances, depending on the complexity of the design tasks, some concurrent engineering environments are linked with domain specific hardware. This hardware can be used to test specific design settings such as balance, thrust, fluid flow, and other functional data. Other domain specific hardware can be used to generate prototype design quickly for review and discussion by the team.

Prototyping Capabilities

Rapid prototyping capabilities allow designs to jump from the drawing board to the real world. By bringing a design into the tangible world designers have the chance to hold and review a model. A designer may be able to see an issue with the design or suggest a creative improvement that may not have been seen until the design was in production, which is often too late to make a substantial change [19].

Experimentation Capabilities

When attempting to meet specific mission requirements, it may be advantageous to test specific design modifications to accommodate these requirements. In these instances, having test hardware such as a wind tunnel, centrifuge, vibration table, and other domain specific hardware will help designers gather data quickly without having to travel far or wait a long time for results. Such an interaction exists at the Georgia Institute of Technology's facility. The test hardware is linked through the server to the concurrent design center [29].

Summary of Hardware Systems for Concurrent Engineering Environments

Like the software, multiple combinations of hardware solutions are deployed at the concurrent engineering facilities around the world and no one solution stands out as the best. The application of the environment drives the required hardware. Establishing the need of the environment is paramount to determining the required number of PCs, displays, audio monitoring equipment, video monitoring equipment, servers and the need for domain specific hardware items. A graphic representation of the hardware included in a concurrent design environment is shown below in Figure 6.

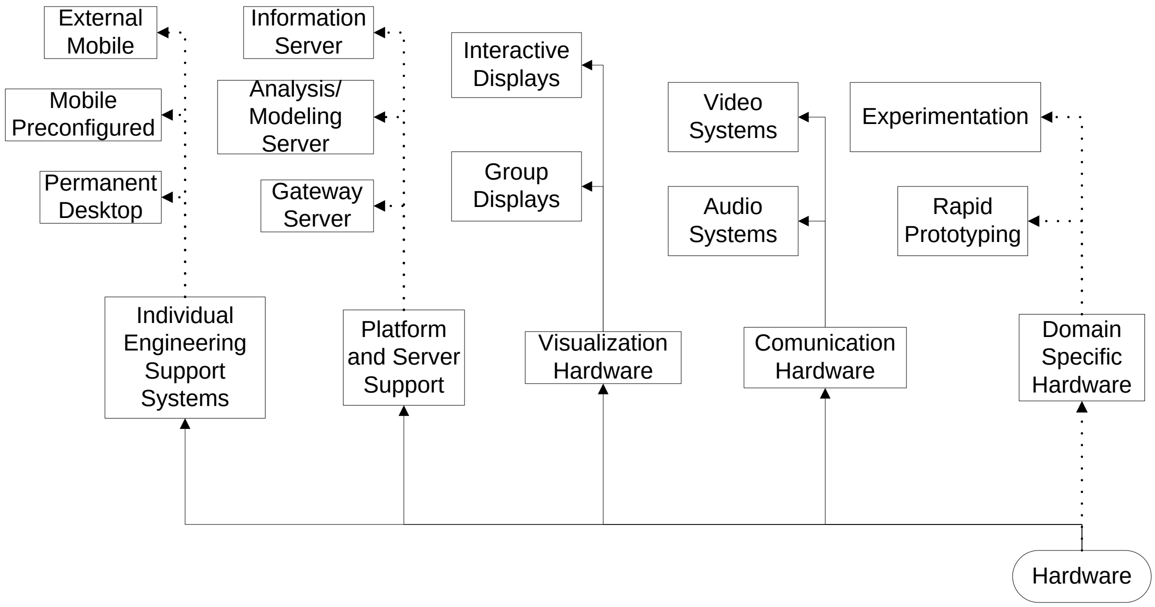

Figure 6: Hardware Decision Tree

The dotted lines represent an "and/or" decision meaning a center could use one or all of the subcategories. The solid line indicates an "and" decision indicating that the particular category of hardware must be included in the setup of a concurrent engineering environment. Each of these decisions must be made to build a well rounded concurrent engineering environment based on the surveyed environments.

CHAPTER FOUR:

CONCURRENT ENGINEERING PEOPLEWARE

Chapters 2 and 3 discussed how software and hardware aid in current engineering, the final key aspect is how human beings interact with each other and the design, peopleware. Ostergaard points out that although engineering design is meant as a technical activity, it truly functions as a social activity [31]. Austin, *et. al.* confirmed that team introductions, pooling of knowledge, and team maintenance accounts for 10-20% of design time [32]. At the heart of concurrent engineering lie five distinct decision areas when establishing a concurrent engineering environment: the roles of the team members, definition of process, team formation strategies, who addresses conflict, and how concurrent is the operation of the environment.

Definition of Roles

Each of the concurrent engineering environments surveyed defined key players and their roles at the outset of the design. The designs performed in the centers vary from center to center but they almost assuredly span a wide range of disciplines; Denton indicates this as a perfect opportunity to utilize collaborative design of experts [33]. A multi-disciplinary team will encounter communication and organizational challenges which must be dealt with before, during, and even after the design [31]. The roles defined by most of the centers are project owners (customers, project managers, and stakeholders), system engineers, various domain specialists, and recorders.

Project Owner

The project owner can be internal such as a project manager within the organization or external such as a customer or stakeholder from an organization hiring a design out. The owner has final purview over the design and is generally the individual who has requested and is funding the research efforts in the environment. Centers vary in the level of interaction required of the project owner during a design session; it ranges from completely hands off to fully engaged and present during a session [34,19,25].

Systems Engineer

The systems engineer is essentially the team leader at each of the concurrent engineering environments. The system engineer provides two of the most important roles in a concurrent engineering environment, they communicate the team, the model, and the customer and they provide the overall leadership and decision making for the center.

The manner in which people lead has been established in the Vroom-Yetton model of leadership styles, Table 1 [35]. The five styles of leadership are defined by who defines the problem and who makes the decision (leader, group, or varies). All of the centers surveyed establish the systems engineer as the leader or co-leader. During Austin's empirical studies of interdisciplinary teams, it was found that a team needs to be led through design activities and that the leader needs to be established at the outset of the activity [32]. Based on this we would anticipate that all centers would have a leader, and they all do, so they tend to emulate one of the first four leadership styles in Table 1.

Table 1: Vroom-Yetton Model of Leadership Styles [35]

Leadership Style	Who Defines the Problem	Who makes the decision
Autocratic	Leader	Leader (may request group input)
Consultive	Leader	Leader w/ group input
Collective	Leader	Group
Participative	Group	Group
Leaderless	Varies	Varies

Collaborative design teams share expertise, ideas, resources, and responsibilities, which, in the case of concurrent engineering environments, are facilitated by the systems engineer [31]. In addition to leadership style, facilitation of communication is another key role for the systems engineer. In Table 2, a collection of issues associated with communication can be seen. The systems engineer must work to mitigate and eliminate impedances associated with these communication issues.

Table 2: Ostergaard's Communication Issues in Collaborative Design [31]

Communication	Mode	*Verbal*
		Textual
		Graphic
		Gestures
	Quantity	*Frequency*
		Duration
	Syntax	*Common Language*
		Translators
	Proficiency of team	*Techniques*
		Technology
	Dependability of resources	*Reliability*
		Availability
	Intent	*Inform*
		Commit
		Guide
		Request
		Express
		Decide
		Propose
		Respond
		Record

Chiu found that the frequency of communication is dependent on the type and scale of the design problems [36]. In the case of concurrent engineering the frequency of communication is driven to one of the highest amounts of any type of design approach. Further, concurrent engineering environments generally foster all modes of communication. Due to the high frequency and large variety of communication there are more causes for delays due impedances and issues, making the system engineer's role of facilitating communication effectively paramount to a successful concurrent engineering session.

Domain Specialists

Bringing together domain experts for each subsystem is a key component of concurrent engineering centers. Every center surveyed made use of domain experts for subsystems, what varied was the number of subsystems or functions assigned to one expert. A domain specialist may have anywhere from 0.5 to 4 subsystems to support. This is determined by the available team size and the availability of expertise to a concurrent engineering center [23,37].

Recorder

When describing the roles of the systems engineer, earlier it was expressed that the communication between the team, model, and customer was important to success. The purpose of the recorder is to document the steps taken and final results of the design for the customer and future reference by the team if necessary. There are two approaches to this. The first is a dedicated recorder to capture all of the changes to the model and thoughts behind them while leaving the domain specialists and systems engineer free to complete the design session [6]. Other centers surveyed relied on the domain specialists to document their steps throughout the design session, leaving the systems engineer to compile the final documentation offline after the session.

Definition of Process

Design Engineering is a procedure driven task generally defined as the process of formulating a plan for the fulfillment of human need through a series of steps including problem definition, conceptualization, embodiment, and detailing [38,39,10,40]. In a concurrent engineering environment which is intent on reducing cost and time of a design while improving the quality of output, the process used is important and should be well defined prior to beginning a design session. Some centers in industry insist on standardizing the activities and processes while others choose the structure for their design activities depending on the design problem.

The type of structure in a concurrent engineering environment includes defining the length of the sessions, the number of sessions required per design, the number of days separating each session, and frequency of concurrent group meetings. When industry concurrent engineering environments were surveyed, they all varied in their approach to structuring the activities. Some indicated the appropriate length for a session is 3-4 hours so as not to burn out the designers and allowing the systems engineer to organize the design for the next session [41]. Others indicate that a full 8 hour day should be worked to pull the most amount of time out of the design [42]. Research in the area is also divided, in research of workshop type environments Austin *et. al.* found that although teams felt they performed better with a methodical approach, there was no evidence that an increase in productivity or success was gained. However, Brusseri and Palmer found a significant positive relationship between the quality of teams' design and process [43]. Parks found that only when the designers did not have familiarity with the design area did a rigorous methodical approach result in a high quality design [44]. Each of these sets of research results depends on the circumstances surrounding the design so we may conclude that the level of design approach definition required varies depending on the design stage and design problem.

Team Formation Strategy

When forming a concurrent engineering team there are a few considerations. The first would be the team size, ranging from eight to thirty by current industry standards; where the domain experts are pooled from, internal to the company or consultants; and whether the team should become a standing team or should temporary teams be formed for each design.

Team Size

Team size is a careful balance between having enough of the correct talent available and having too many people in the way of progress. Willaert noted that teams too great in number may become unmanageable and require too much support while a team's creativity may be stymied if too small [45]. Research has indicated that in order to facilitate problem solving, decision-making, and spontaneous communication a team size should be kept between six and fifteen [46,47,48]. In general, the team's size should match the scope and complexity of the design task, so getting this level of manning correct is important to the quality of the results as well as the overall cost of the design [49,45].

Internal Teams

There are pros and cons to internal teams. The pros are the quick access to required personnel, mitigated risk of information protection, and familiarity to the company's tools, methodologies, and expectations. The cons would be the large staffing requirements for multiple industry and discipline support, and the experts in house may not be the best available for the job. Many existing concurrent engineering environments staff all of the required expertise in house; generally the designs that are performed are very similar in nature [50].

Consultative Teams

Consultative teams are very beneficial when the designs in a concurrent engineering environment are dissimilar. In these cases, outside experts can be brought in to fill a role that may only be needed for a small portion of a man year. The cons to a using a multitude of consultants is the lack of familiarity with internal operations and tools, availability of experts and the scheduling issues that follow, and protection of intellectual property in regards to the internal tools and designs of either the designer or the company [51].

Standing Teams

A standing team can be very beneficial when numerous design studies are conducted in close succession to each other. JPL has gained recognition for the success of Team-X, their standing research team. They perform numerous studies, 57 per year, each of which is very similar in nature to the previous. Additionally, standing teams will become familiar with each other over time allowing for personal connections to be made and facilitating conflict resolution [5].

Temporary Teams

Temporary teams have the benefit of a finite term of service. If these teams are pulled together from a pool of people which have other roles in a company, then the focus of that designer may become an issue if the requirements of either role become too great. Further, the retreat or workshop type atmosphere may be a welcome change for a short while but become an overburdening paradigm shift over time [51].

Conflict Resolution Strategies

Maier and Sashkin wrote about resolving differences in opinion between leaders and subordinates [52]. They note that this difference in final decision preference can lead to one of four outcomes: victory for one side or the other, compromise, or the generation of an "integrative alternative" [52]. This "integrative alternative" differs from a compromise in the fact that it is a generated independent solution while a compromise is a portioned combination of previously posed solutions. Maier and Sashkin further explain that earlier research indicates that the integrative alternative is often the best outcome because, among other reasons, it involves a solution that everyone can agree on. From this reasonable assumption, Maier conducts an experiment to confirm that leaders can actually be trained to promote group discussion and idea generation rather than trying to convince the group that the leader's decision is the best [52,53].

Degree of Concurrency

Based on the theories and goals of concurrent design, a team with very little geographic and temporal dispersion may be desired. Garner conducted research to compare the graphic communication of distributed teams to those of collocated design teams. He found that remote designers spent 51% more time making drawings, sketches, and other graphics than their collocated counterparts; however, the actual production of drawings and sketches, decreased significantly when teams were distributed [54]. The degree of concurrency varies in industry concurrent engineering environments from completely concurrent to completely distributed. This is driven largely by preferences, intended purpose of the environment (to support industry, government, or to teach), and availability of talent [51,37].

Summary of Peopleware for Concurrent Engineering Environments

Ostergaard points out that although engineering design is meant as a technical activity, it truly functions as a social activity [31]. Accepting this as true, then the formation and facilitation of the encounter between people within the concurrent engineering environment is vital. Determining the desired focus to support industry, government, and/or to teach determines how teams are formed and design sessions are executed. A graphic representation of the peopleware included in a concurrent design environment is shown below in Figure 6.

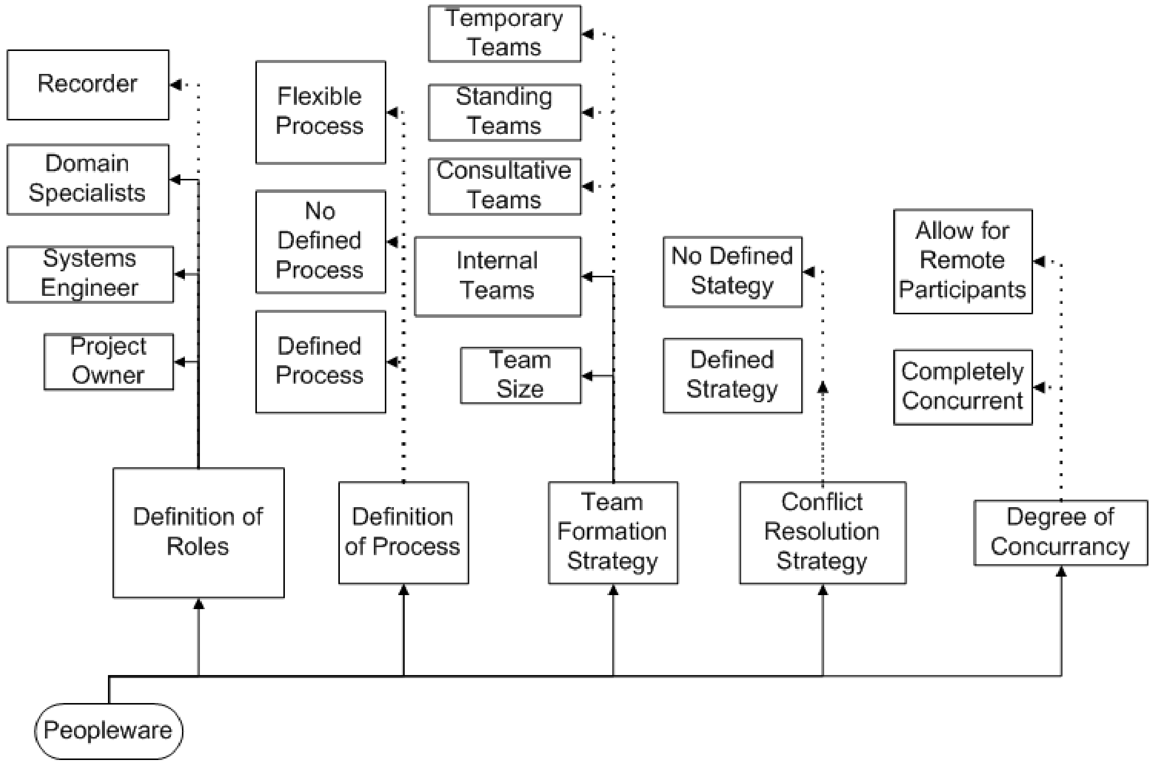

Figure 7: Peopleware Decision Tree

The dotted lines represent an "and/or" decision meaning a center could use one or all of the subcategories. The solid line indicates an "and" decision indicating that the particular category of hardware must be included in the setup of a concurrent engineering environment. Each of these decisions must be made to build a well rounded concurrent engineering environment based on the surveyed environments.

CHAPTER FIVE:

SURVEY OF EXISTING CONCURRENT ENGINEERING ENVIROMENTS

Concurrent engineering environments are located around the world at government, academic, and industry locations. Although an interactive site visit would be preferred the following is a literature review and comparison of practices at each center. The centers considered are:

- Product Design Center (PDC) at Jet Propulsion Laboratories [9,5,25,41]
- The Aerospace Systems Design Laboratory (ASDL) at Georgia Technical Institute [29,18,55,56]
- The Concept Design Center (CDC) at the Aerospace Corporation [34,24,7,57]
- The Space Research and Design Center Laboratories (SRDC) at the Navy Postgraduate School [58,24,34]
- Concurrent Design Facility (CDF) at European Space Agency [19,23,50,59,60,6]
- Integrated Concept Design Facility (ICDF) at TRW [37]
- Space Systems Analysis Laboratory (SSAL) Concurrent Engineering Facility at Utah State University [26]
- Integrated Missions Design Center (IMDC) at NASA Goddard Space Flight Center [51]

- Space System Rapid Design Center at Ball Aerospace and Technologies Corporation [8]
- Satellite Design Office (SDO) at Dornier Satellitesysteme (DSS) [61]
- Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology [25]
- Space System Concept Center (S^2C^2) at Technical University of Munich [25]
- Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT [25]
- The Center at Boeing Military Aircraft Company [25]
- Human Exploration and Development of Space Integrated Design Environment (HEDS-IDE) at Johnson Space Center [25]

Some of the centers listed above took great care to elaborate on the hardware, software, and peopleware used in the environment while others failed or chose not to provide a full set of operational details. The Descriptions are based on the best information available and should be followed by a site visit to each center for verification and expansion of details.

Jet Propulsion Laboratories' Product Design Center (PDC):

The Jet Propulsion Laboratory (JPL) established the Project Design Center (PDC) in 1994 for the purposes of developing and implementing new tools and processes centering on concurrent engineering for space systems [9]. A layout of the Team-X PDC can be seen in Figure 8.

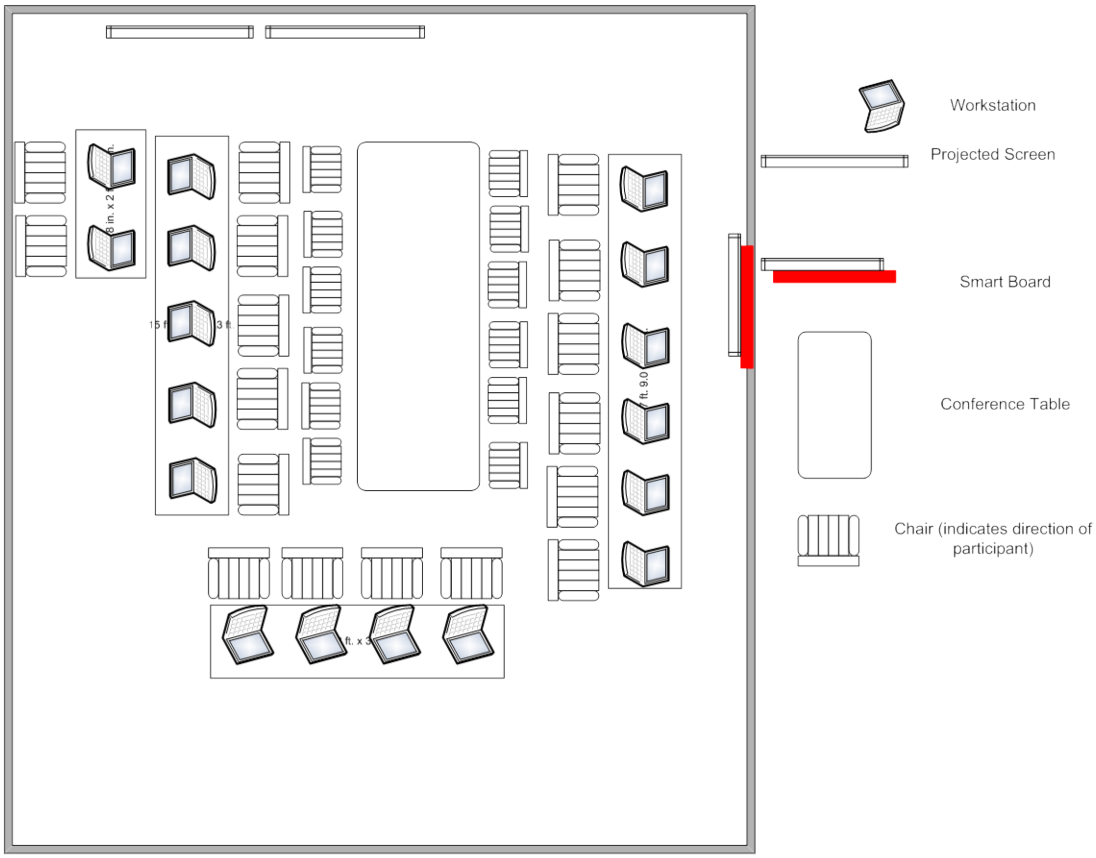

Figure 8: Team-X PDC Layout [25]

The objective of the PDC is to fulfill NASA's "Cheaper, Better, Faster" paradigm introduced by Goldin in the early 1990's. JPL believed that the PDC environment would enhance the concurrent engineering methodologies used in design [5]. The PDC makes use of two types of expert teams, Team X and Team 1 [25]. Team-X, originally Advanced Products Development Team, was created by the JPL Advanced Planetary Missions program office in 1995; their role is to perform conceptual mission studies and concept design studies [5]. Team 1 was developed to perform general studies and develop proposals for JPL [25].

JPL has realized great success in the implementation of the PDC. By introducing the Integrated Product Teams (IPT) early in the design process the downstream risk of unaccounted for issuse are minimized. The design tools that are commonly utilized are readily available and presented in a consistent format to the designers real time, reducing design time. JPL utilizes long standing design teams allowing for learning on the job and familiarity benefits. Cost experts are included early in the design process establishing cost as a primary and foucused metric. Lastly, JPL believes in and supports the PDC and the design teams lifting the concern of support from the designers [5].

PDC Hardware

The hardware at the PDC has been setup to fit the needs of each domain specific workstations. In general 16 Windows and 4 Linux desktop computers are installed at each of the fixed workstations. Additional kiosks are available for guests with their computers. All computers are linked with a local, dedicated file server. Two screens are located at the front of the facility which are controlled by the project manager and can display any of the screens in the facility [41].

Audio and video conferencing equipment is also available in the facility to communicate and document the design sessions. These are integrated via the internet to support external discussions as well as internal documentation [41]. A visual representation of the PDC hardware layout can be seen in Figure 9.

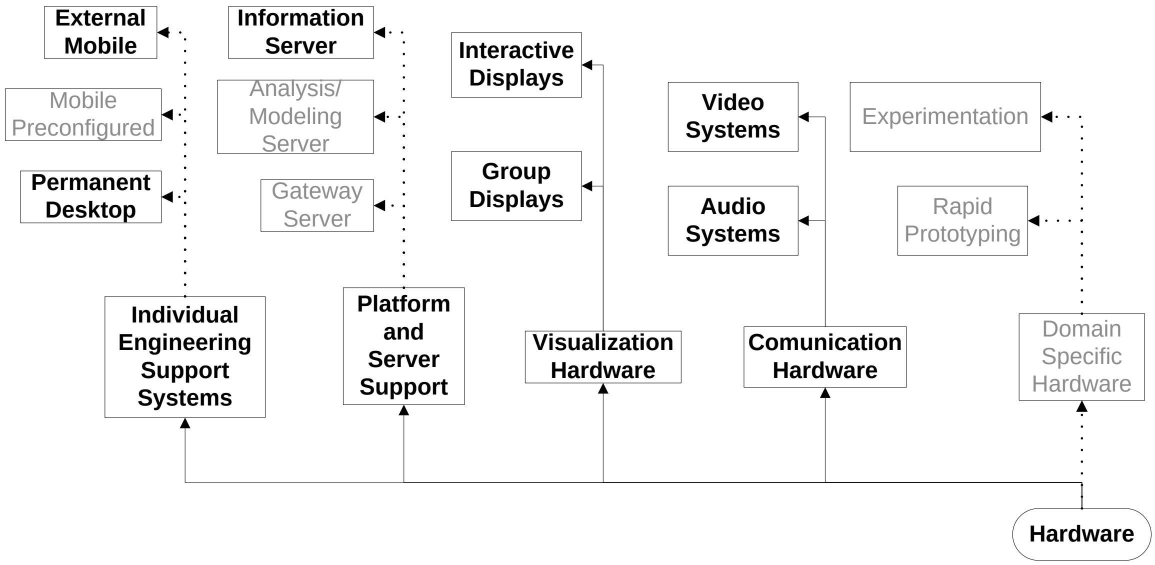

Figure 9: PDC Hardware Configuration

PDC Software

Excel based integration technologies are used to pull information from each design discipline into the systems model [25]. Standard MS Office suites are used for documentation and communication. Domain Specific software is used by individual disciplines and is listed below by discipline in Table 3.

Table 3: PDC Domain Specific Software

Domain	Tool Used
Optical Analysis	LightTools, ZeMax, TracePro
Structural Design and Analysis	Pro-E, NASTRAN
Thermal Design	Sinda, Tranlysis
Radiometry	Custom Designed Spreadsheets
Programmatic	MS-Project

Due to the complex problems the PDC is required to solve, the center must maintain a host of domain specific software tools which have complex interactions, seen in Figure 10 [5]. In Figure 11 the PDC's choices in software and level of customization can be found.

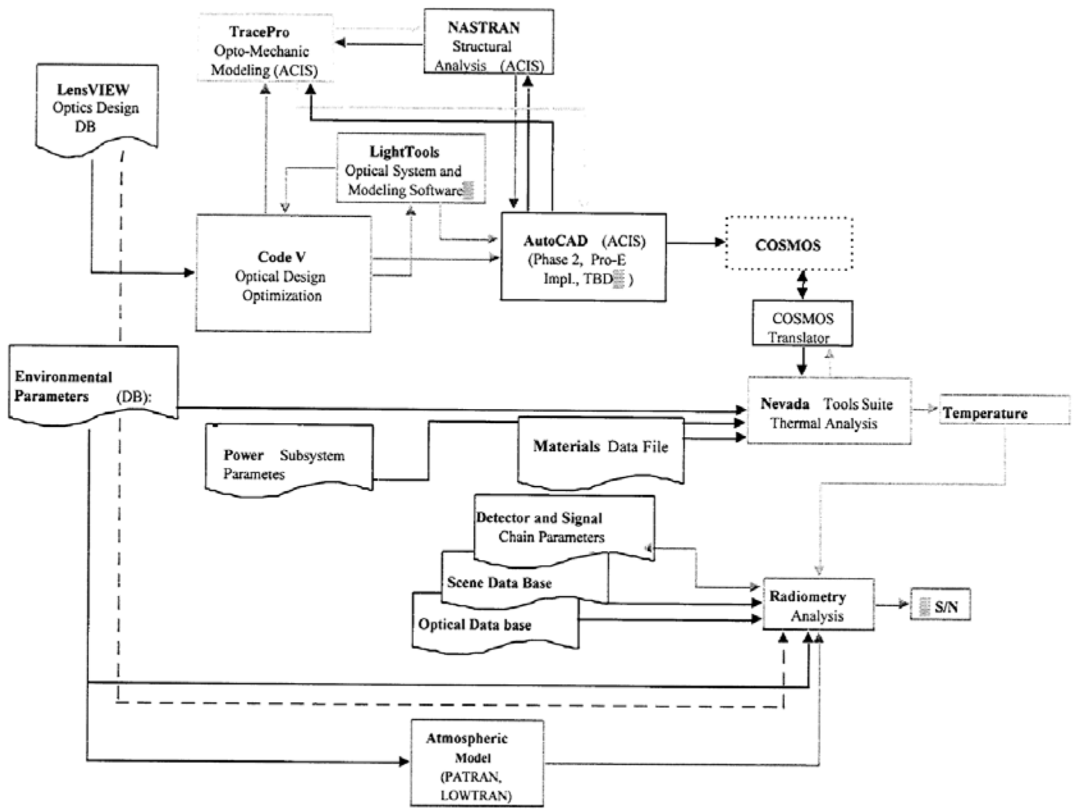

Figure 10: PDC Optical Software Tools [5]

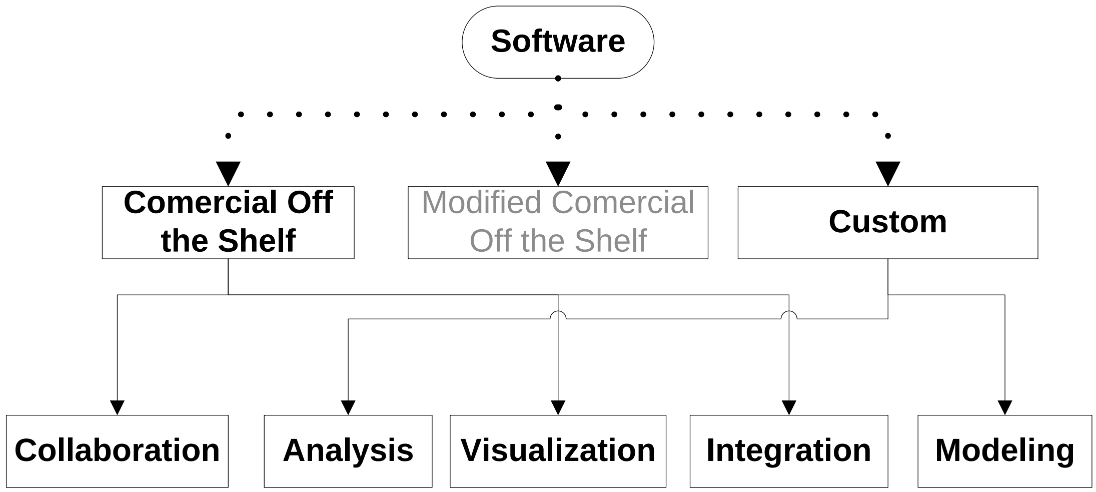

Figure 11: PDC Software Configuration

PDC Peopleware

Teams are formed for focused purposes from a pool, those noted as experts in their field. Each field is staffed by a primary and secondary expert incase availability becomes an issue or a staff changes removes one of the field experts. The sessions are run for at most three hours for as many days as the design complexity warrants. Several days generally separate each session to allow offline data gathering [9]. The PDC design process is well defined an can be seen below in Figure 12.

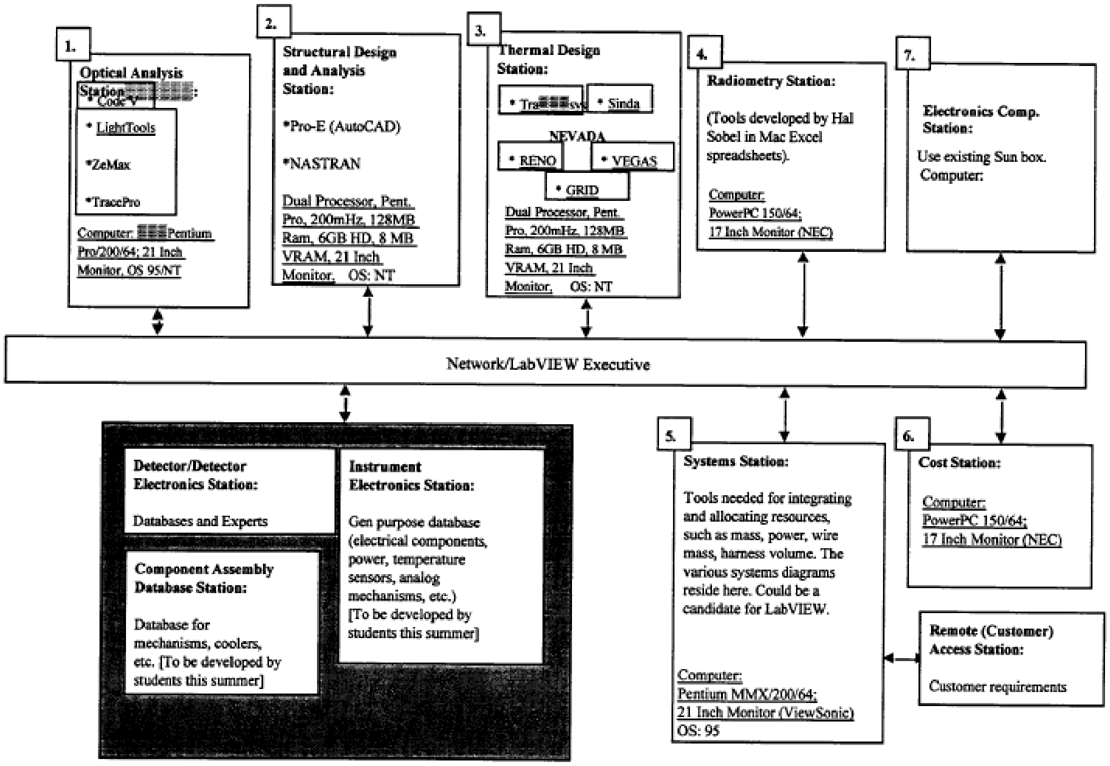

Figure 12: PDC Process Flow Chart [5]

Each discipline the project manager requires for the session must be present for a design session to continue, if a discipline requires time offline to verify data, the session stops. The use of permanent teams is used to maintain continuity and achieve full coverage of each discipline at each design session. It is also required that designs be processed rapidly into figures and charts that can be used to make decisions, otherwise this process is not appropriate [5].

The PDC operates during one of two three hour sessions during the day. A customer books any number of sessions depending on the complexity of the task but JPL requires at least 2 sessions seperated by several days even for the most minor design task.

Before the sessions start, the customer interacts with the Team-X leader to discuss the mission and tasks Team-X will be given. The first session is generally focused on satisfying the customer requirements in an initial concept design. The subsequent sessions attempt to refine the initial concepts usually to reduce cost or focus in on better defined customer wants. Since the customer is required to attend the session, his voice becomes part of the design. [5] A defined conflict resolution strategy could not be found for PDC. The peopleware configuration can be seen in Figure 13.

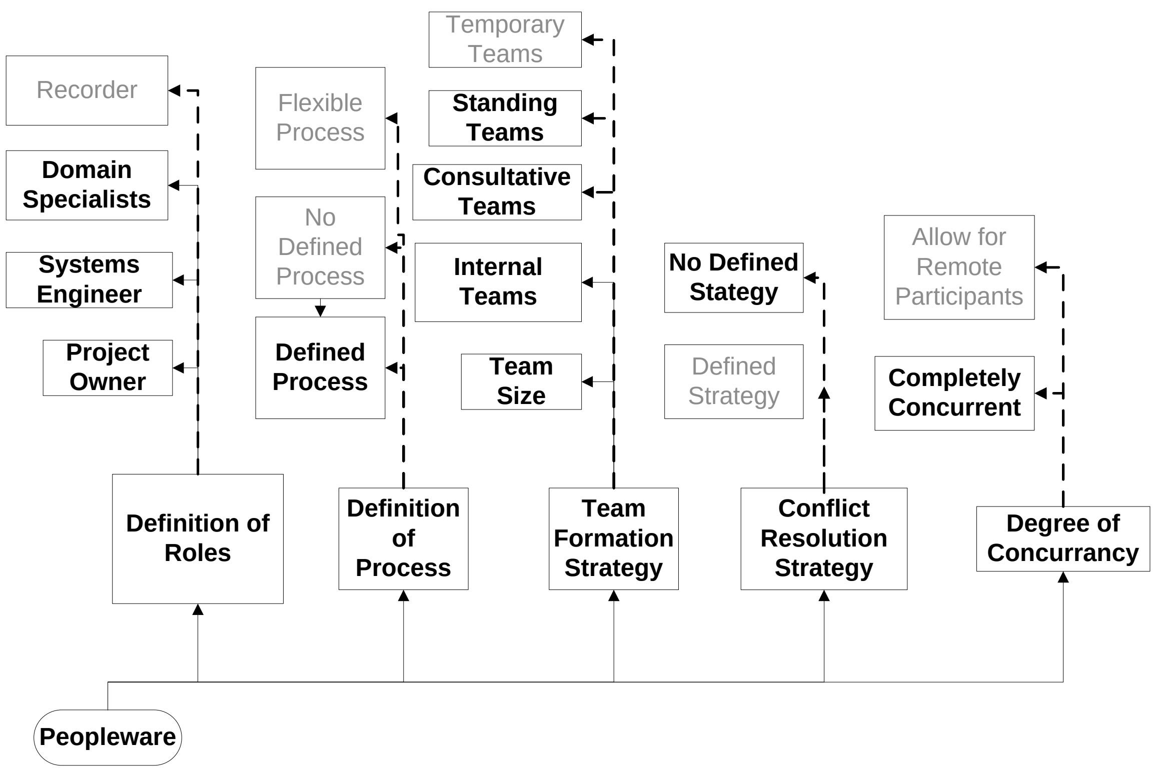

Figure 13: PDC Peopleware Configuration

<u>The Aerospace Systems Design Laboratory (ASDL) at Georgia Institute of Technology:</u>

The Aerospace Systems Design Laboratory (ASDL) was established at Georgia Institute of Technology in 1992. The ASDL now consists of three key facilities: the

Collaborative Design Environment (CoDE), the Collaborative Visualization Environment (CoVE), and Computational Resources (CoRe). These three facilities combine to form the collaborative engineering environment used to design aerospace solutions for multiple customers and teach students methods and applications of concurrent and collaborative engineering. A representation of the ASDL environment can be seen in Figure 14.

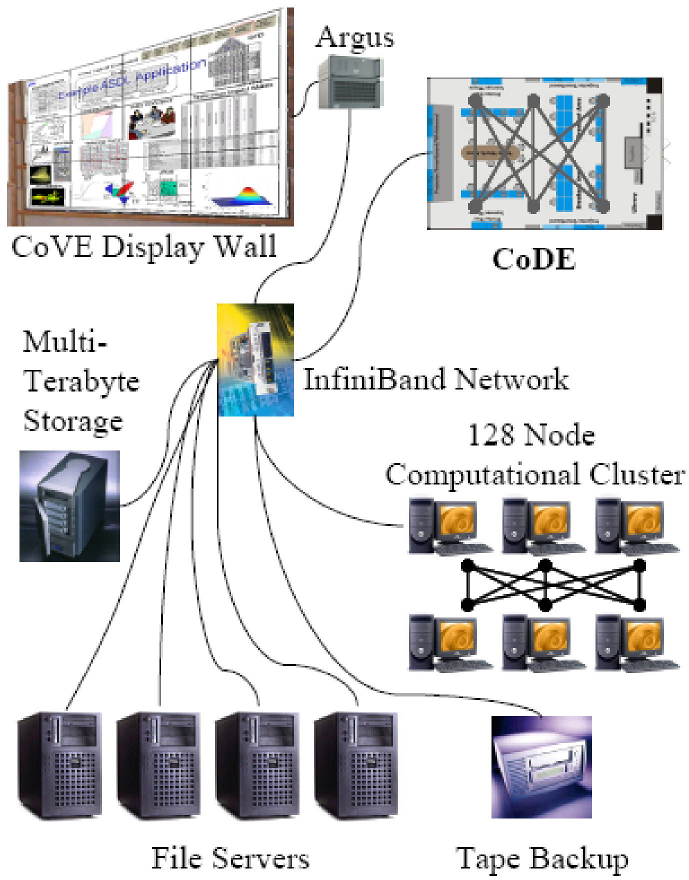

Figure 14: ASDL Design Facilities [29]

The objective of CoDE is to rapidly execute collaborative design conceptualizations by fostering designers' creativity in multidisciplinary design teams [29]. The environment set out with two missions: "Enhance the fidelity of simulation models for design space exploration and robust design methodologies," [29] and "create a national asset for the development of next-generation conceptual design facilities and approaches" [29].

ASDL Hardware

Where ever possible, Commercial of the Shelf (COTS) hardware was purchased to minimize additional costs and utilize existing support availability. Standard desktop personal computers are installed at 8 workstations in the team area and three in each breakout area. They are linked to standard LCD projected displays and SMART boards using multiple input/output signal distribution. LCD touchpads are also used at the workstations to allow sketching. The computers are each linked to printers and scanners to allow for the output and input of paper artifacts to the common design knowledge pool. Webcams are also installed to allow for remote collaboration from the environment and between the CoDE and CoVE. IP Phone systems, also all for communication through the network and add features such as recording of conversations, portability of numbers, and email voice messaging [29].

The CoRe can be considered the brains behind the environments. The CoRe is a computational cluster of 256 processors with a 7 Terabyte storage subsystem and Infiniband high-speed network [18]. The Infiniband is a high bandwidth, low latency network that allows switch networking between computational resources [55]. This cluster allows the facilities at ASDL to communicate with each other quickly to support real time physically based collaborative design [18]. The hardware configuration can be found in Figure 15.

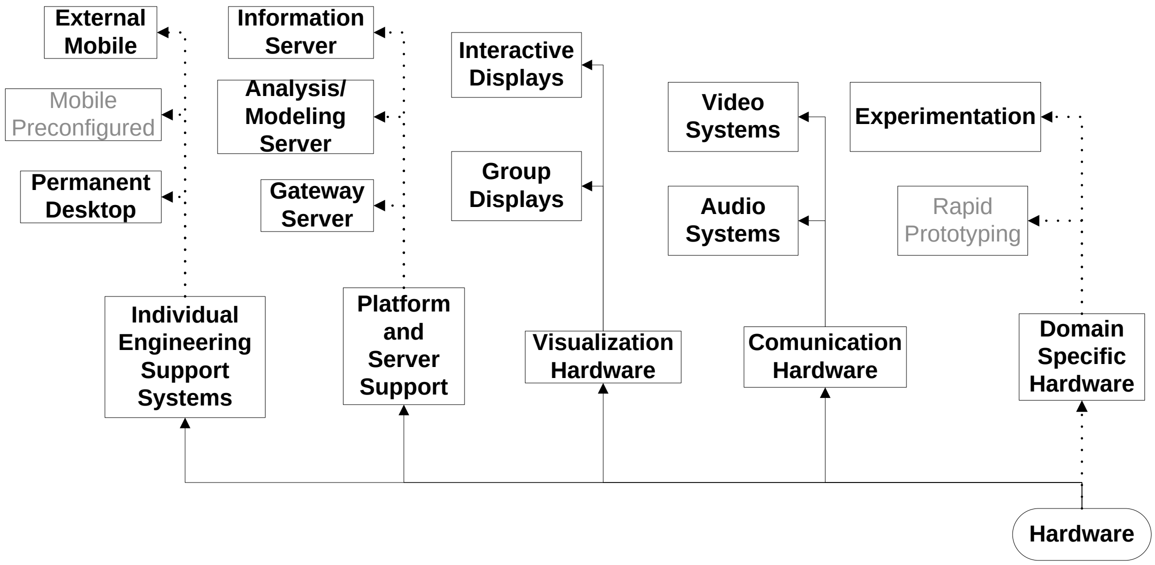

Figure 15: ASDL Hardware Configuration

ASDL Software

The ASDL makes use of COTS software tools and Higher Fidelity domain specific tools as needed. All of the PC's are loaded with the MS Office Suite which is used to handle the documentation, cost analysis, and model generation. A list of other domain specific software used is listed in Table 4 by function.

Table 4: ASDL Domain Specific Hardware

Function	Tool Used
Statistics	JMP
Monte Carlo Plug-in	Crystal Ball
Mathematical Analysis	Matlab
Code integration/automation	Model Center
Programmatic	MS-Project

The ASDL software configuration can be found in Figure 16.

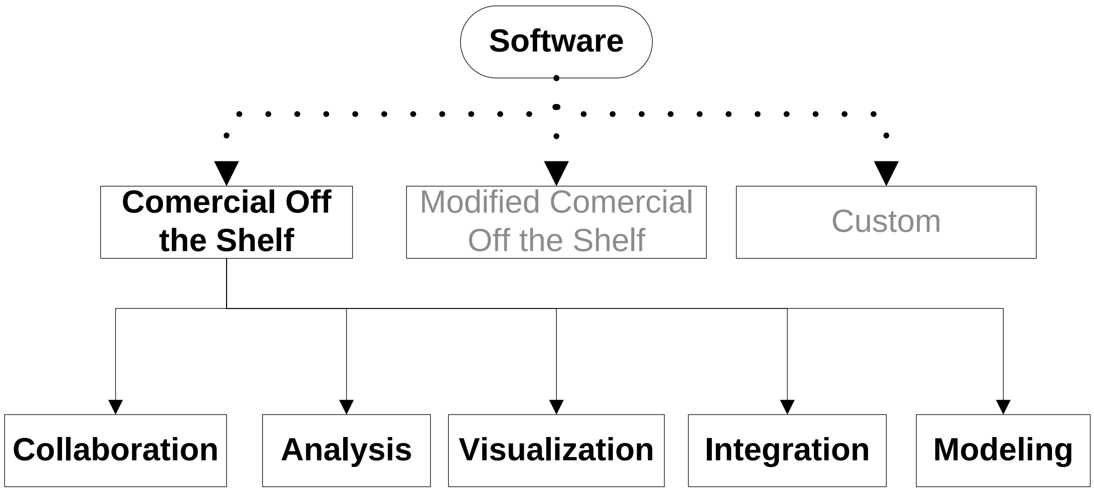

Figure 16: ASDL Software Configuration

ASDL Peopleware

Research has taken place in CoDE to establish appropriate hardware, software, and peopleware for their operations in aerospace. This research has been used to improve the environment, train, and teach. The CoDE utilizes a modular floor plan consisting of a team work area, a library, and two breakout areas with movable curtains allowing the flexibility to expand the team area or run competing designs experiments; A floor plan of CoDE is shown in Figure 17.

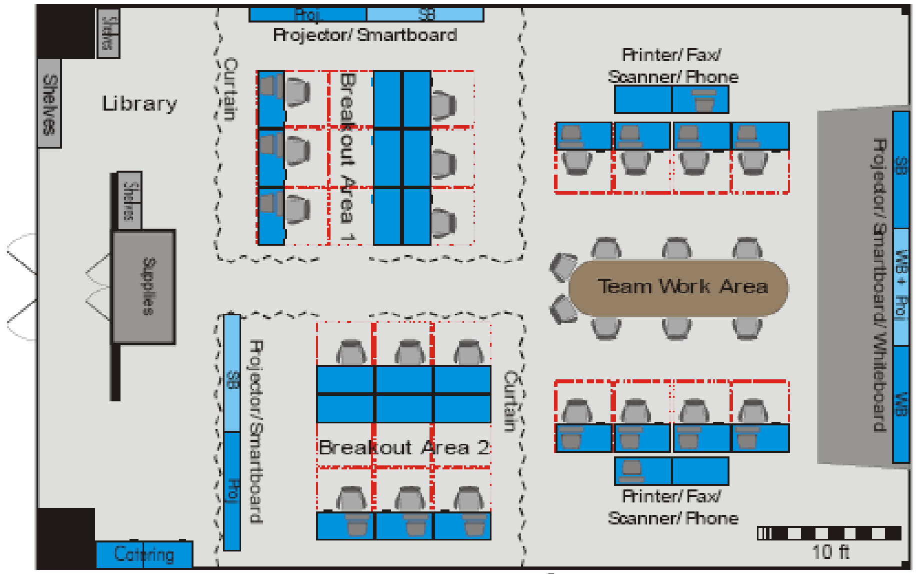

Figure 17: ASDL: Floor plan of the CoDE [62]

In conjunction with CoDE, CoVE is used for visually intensive portions of the design. The CoVE consists of 24 workstations and a multimedia wall driven by a high performance PC cluster which can be linked to the CoDE. In Figure 18, a photograph and layout of the CoVE can be seen [29].

CoDE has moved away from the spreadsheet based data exchange models and is developing state of the art real time physics-based, high-fidelity models. Using products like I-Sight, multiple domain specific tools can be integrated together to generate a more real time model [56]. The computational requirements are exponentially higher in order to accomplish these models. The center is used for multiple purposes: design for government customers, design for industry customers, and engineering education. As such, the process is not held as ridged as other centers and changes from application to application.

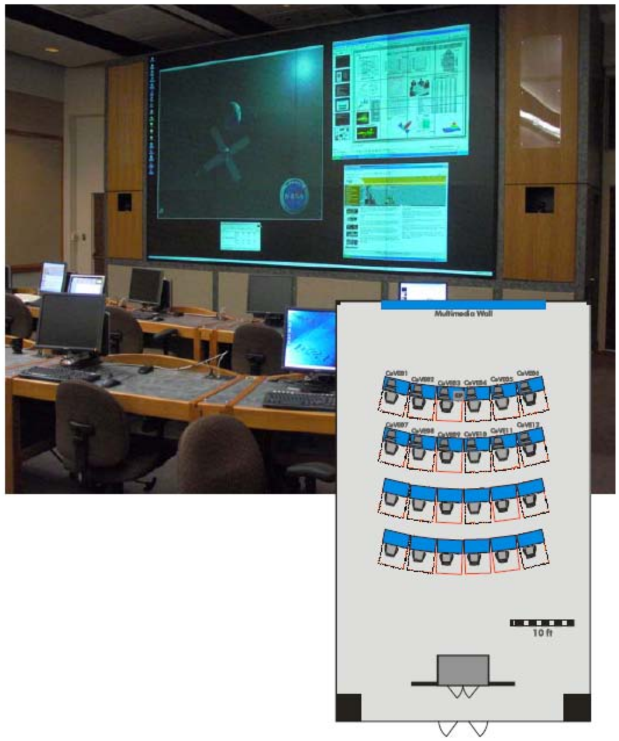

Figure 18: ASDL: CoVE Layout

The ASDL facility boasts a flexible process that allows for internal use as well as consultative participation with temporary teams formed for each specific design [63]. ASDL defines the subsystem representation required for an aerospace design but allows for additional members to participate outside of the predefined roles [18]. A dedicated recorder is used to homogenize the design details to the customer [29]. The audio and video capabilities of the facility are in centralized locations in the CoDE but fully integrated in the CoVE allowing for video and audio teleconferencing in both areas but recording capabilities only in the CoVE [29,63]. The peopleware configuration can be seen in Figure 19.

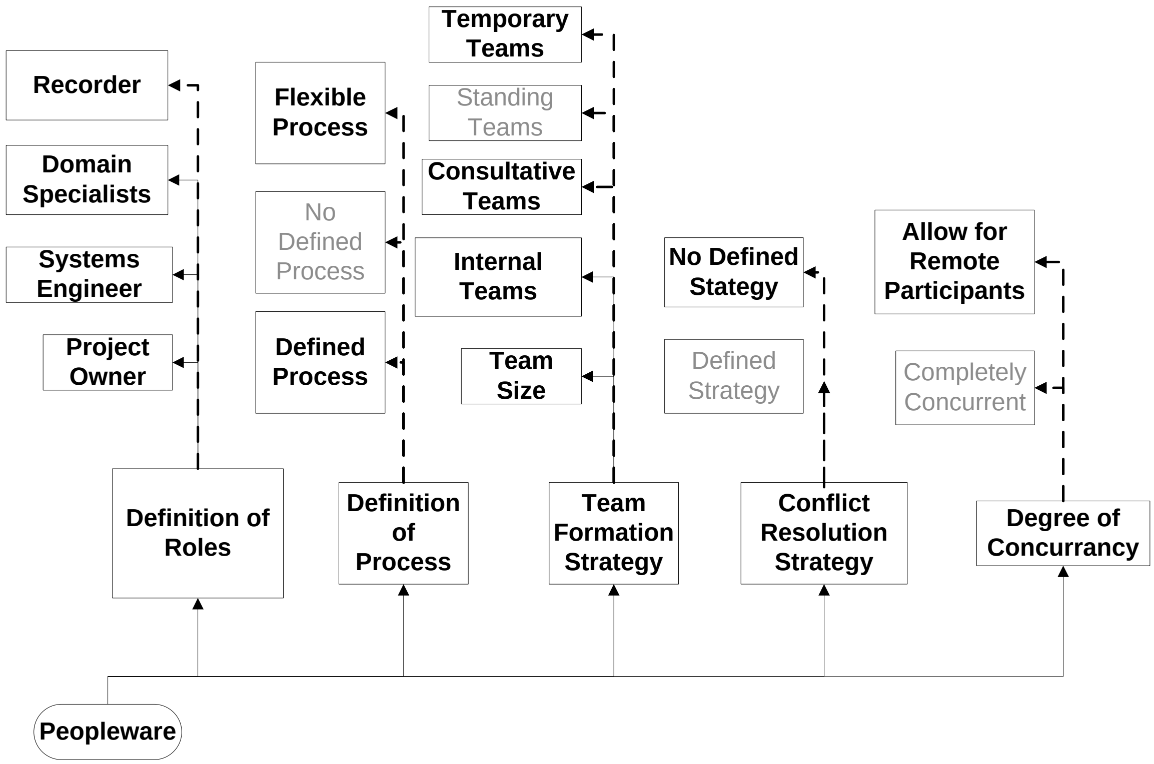

Figure 19: ASDL Peopleware Configuration

<u>The Concept Design Center (CDC) at the Aerospace Corporation:</u>

The Aerospace Corporation's Concept Design Center (CDC) was established in 1997. The Aerospace Corporation is an independent, nonprofit company who serves as an objective participant in technical analyses and assessments of national, commercial, and civil space programs [57]. The CDC was founded around three key concepts:

- A team based on engineering expertise and experience.
- A process using real time, flexible design tools enabling quick results
- A facility which enables easy team and customer interaction [24].

These concepts are used as part of a concurrent engineering process which enables rapid generation of spacecraft design. By bringing together lessons learned, experience, rules of thumb, algorithms and analysis, the CDC can be used for trade studies, technology insertion assessments, and conceptual designs [24]. These tools and approaches allow for the end to end linking of design parameters, rapid iterative calculations, and interconnectivity of cost calculations [7]. Since the founding of the CDC, the Aerospace Corporation has reduced the time and cost required for spacecraft design by up to 70% [24].

CDC Hardware

The CDC has 13 personal computers all linked to a dedicated server for quick data exchange [7]. The computers are located around the outside of the room with a conference table and chairs located in the center. Two projectors are used in the main room focused towards the front wall driven by a touch screen interface allowing any two computer monitors to be shown at any given time. A separate conference table, personal computer, and projector are located in the room and can be portioned off by a movable wall. All of the computers are linked to a copier and printer located in an adjacent support room [24]. This is all shown in Figure 20.

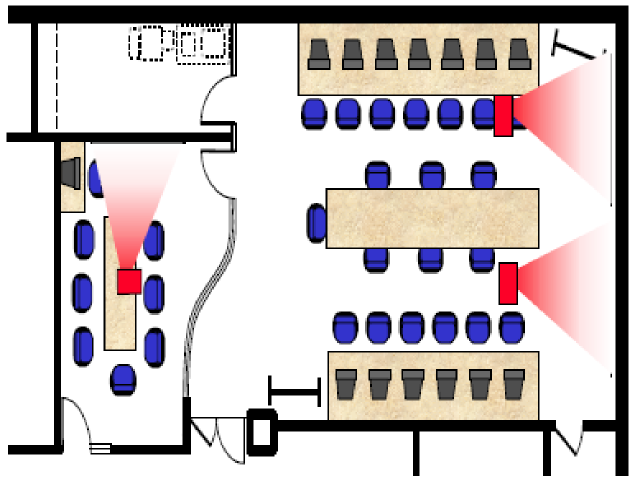

Figure 20: CDC Layout [24]

The hardware configuration for the CDC can be found in Figure 21.

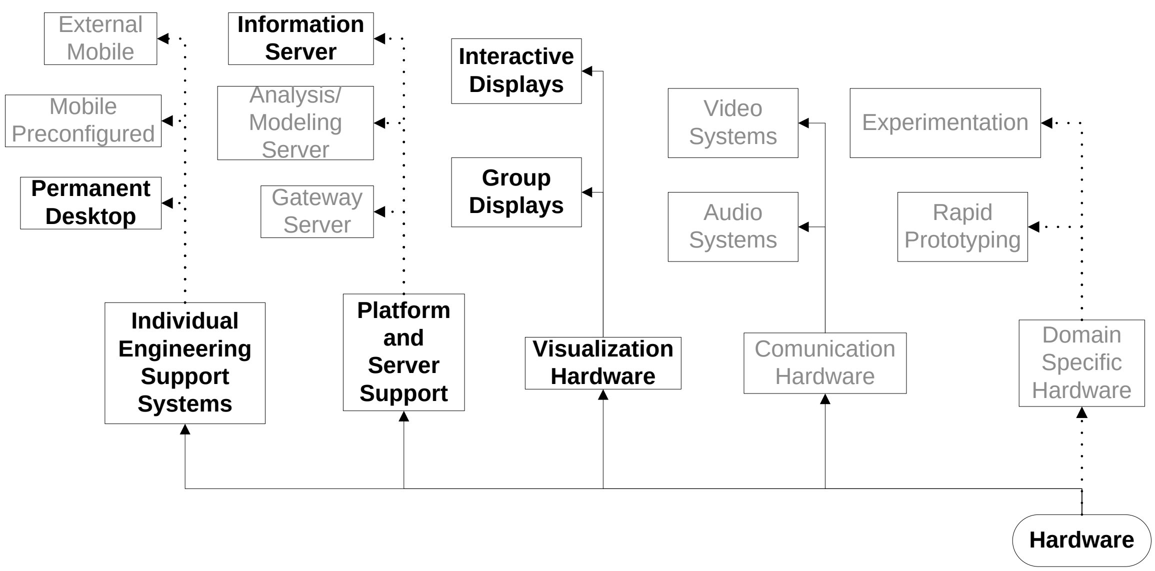

Figure 21: CDC Hardware Configuration

CDC Software

All of the PC's in the CDC have the standard windows based office packages to include MS Word and Excel. General software was chosen based on familiarity for all team members and ease of connectivity. This flexibility is required as the CDC is tasked with the design of customized spacecraft for specific missions. Ease of connectivity is important, and the foundation, of the concurrent design process [7].

Each domain at the CDC uses databases of commercially available and previously designed articles for component selection. The key design parameters of these components; mass, size, cost, etc.; are stored in the databases which are then linked to MS Excel based spreadsheets. Custom designed Visual Basic interfaces allow the systems engineer to control the flow of information.

Some PCs have additional software depending on which domain occupies them during a session. For the domains that require solid modeling, SolidWorks is installed. Those dealing with controls and payloads require the use of PCSOAP, an orbital analysis program. [24] A list of domain specific software is shown below in Table 5.

Table 5: CDC Domain Specific Software

Function	Tool Used
Solid Modeling	SolidWorks
Orbital Analysis	PCSOAP
Code Integration	Visual Basic
Programmatic	MS-Project

The Software configuration at the CDC can be found in Figure 22.

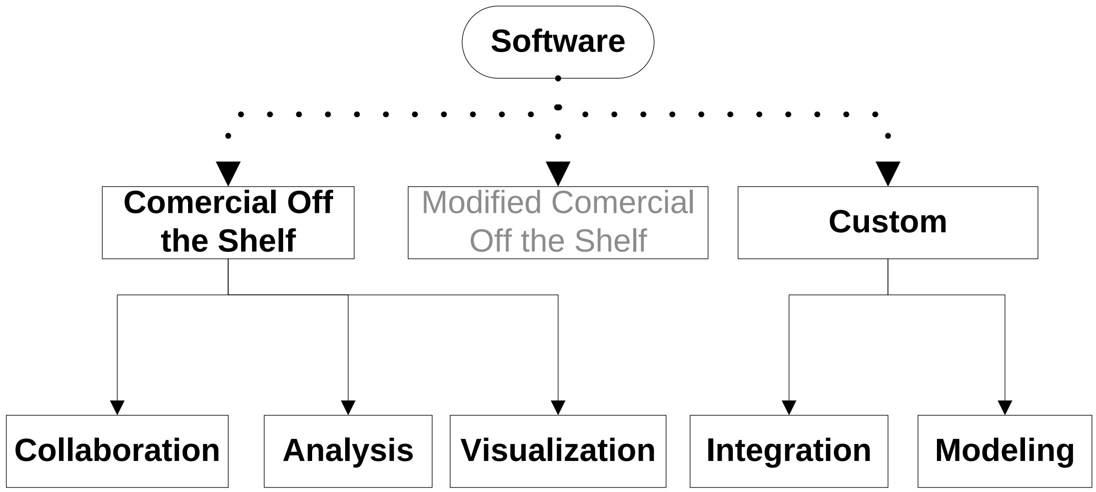

Figure 22: CDC Software Configuration

CDC Peopleware

The CDC consists of ad hoc teams for specific sections of a mission, if the mission requires a function its team must be present during the design session. The various functions are shown in Figure 23 [7].

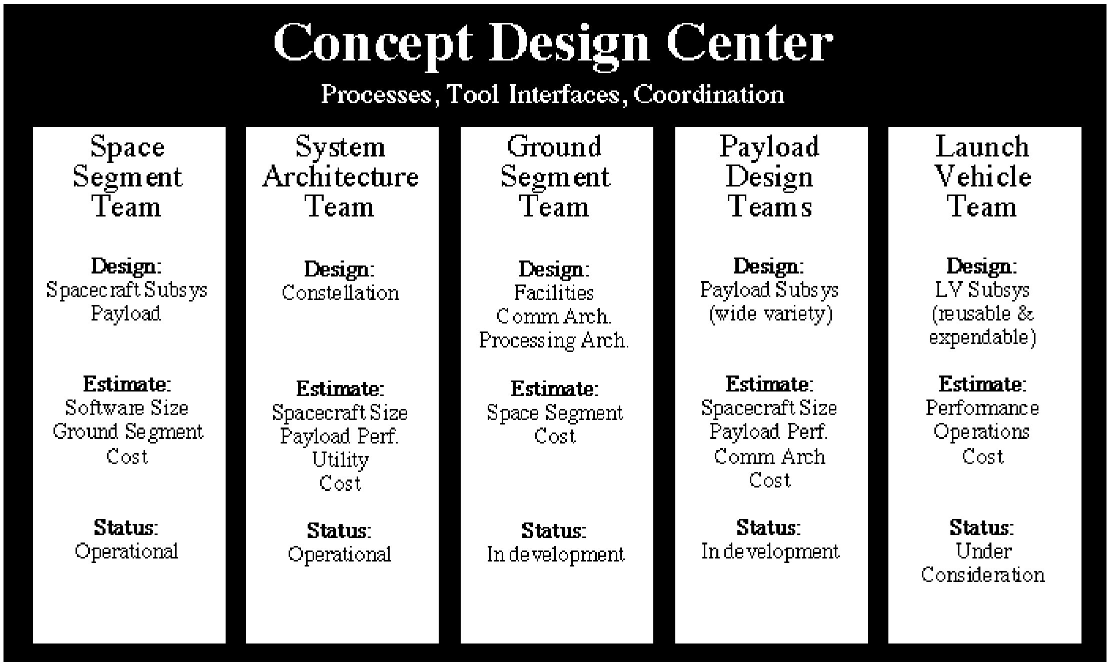

Figure 23: Functional Teams [7]

The typical CDC study consists of three distinct stages: study planning, one or more CDC design sessions, and post-CDC session wrap up. In the first stage, the team leader discusses the design task with the customer to establish mission requirements. This is used to choose a team for the design. The CDC uses an ad-hoc team structure that does not require a long term commitment. The team members are volunteers and are rotated in an out of use so as not to burn out the designers. Sessions are real time and require team member participation at all stages [24].

In the second stage the CDC team establishes an initial design by operating within subsystem MS Excel worksheets that roll up into a system model, defining cost, mass, payload, and other key design parameters. This is iterated until a suitable design is found and then the project moves into the final documentation stage. The reporting of each subsystem is the responsibility of the individual designer and usually takes 3-4 weeks to complete for the customer [24]. The peopleware configuration of the CDC can be found in Figure 24.

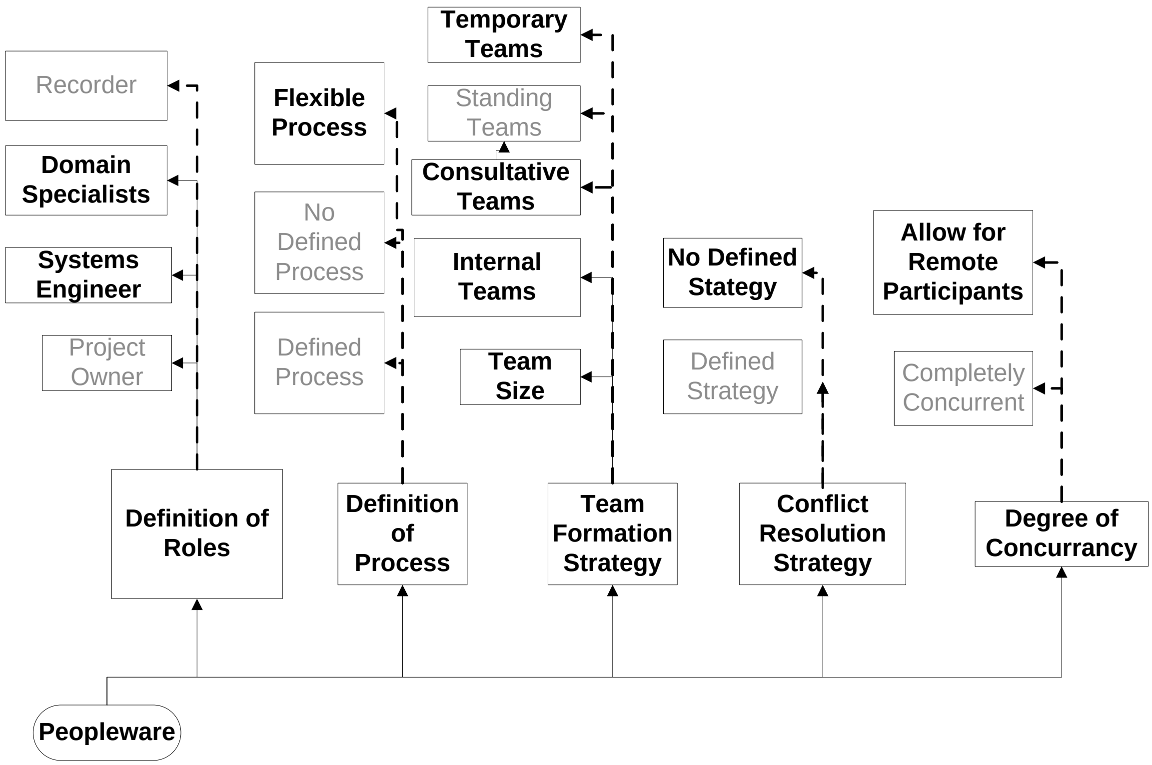

Figure 24: CDC Peopleware Configuration

<u>The Space Research and Design Center Laboratories (SRDC) at the Navy Postgraduate School:</u>

The Space Research and Design Center Laboratories (SRDC) is part of the Navy Postgraduate School in Monterey California. The SRDC consists of 5 separate research laboratories: Spacecraft Design Laboratory, Adaptive Bean Control Laboratory, Smart Structure and Attitude Control Laboratory, FLTSATCOM Laboratory, and Bifocal Relay Mirror Spacecraft Laboratory [58]. All five laboratories are used in collaborative/concurrent design; however, the SRDC uses the Spacecraft Design Center (SDC) as their Concurrent engineering environment, shown in Figure 25.

Figure 25: Spacecraft Design Center (SDC) [58]

The focus of the SRDC is instruction and research in space system engineering and space operations. They have executed joint Department of Defense projects with Satellite Operational Center, NRL, AFRL, ONR, Lockheed Martin, and Boeing. The laboratories also give students hands on research opportunity to design, analyze, and test space systems [58].

SRDC Hardware

The SRDC is comprised of 9 desktop workstations and one laptop computer. The laptop is used to operate a central projector. A server, named *Endeavor,* is linked to the workstations via an internal network. One projected screen is located at the front of the room linked only to the team leader's laptop [34].

The other 4 laboratories at SRDC contain multiple domain specific hardware items used for modeling/testing space based issues/solutions. The hardware includes an optical relay mirror for research on acquisition, tracking, and pointing of spacecraft. A three axis simulator is used in the simulation of space flight of optical components. The Laser Jitter Control Test-Bed is used to investigate and reduce optical jitter in changing enviroments.

The Adaptive Optics Test Bed is also used to improve the control of optics in space flight. The qualification model of the Navy FLTSATCOM comunications satelite is located at SRDC and is used for simulating attitude control and output. The Flexible Spacecraft Simulator simulates attitude motion in the pitch axis. Finally, the precision pointing Hexapod is used to test controls for fine steering and vibration isolation [24]. The hardware configuration or the SRDC is shown in Figure 26.

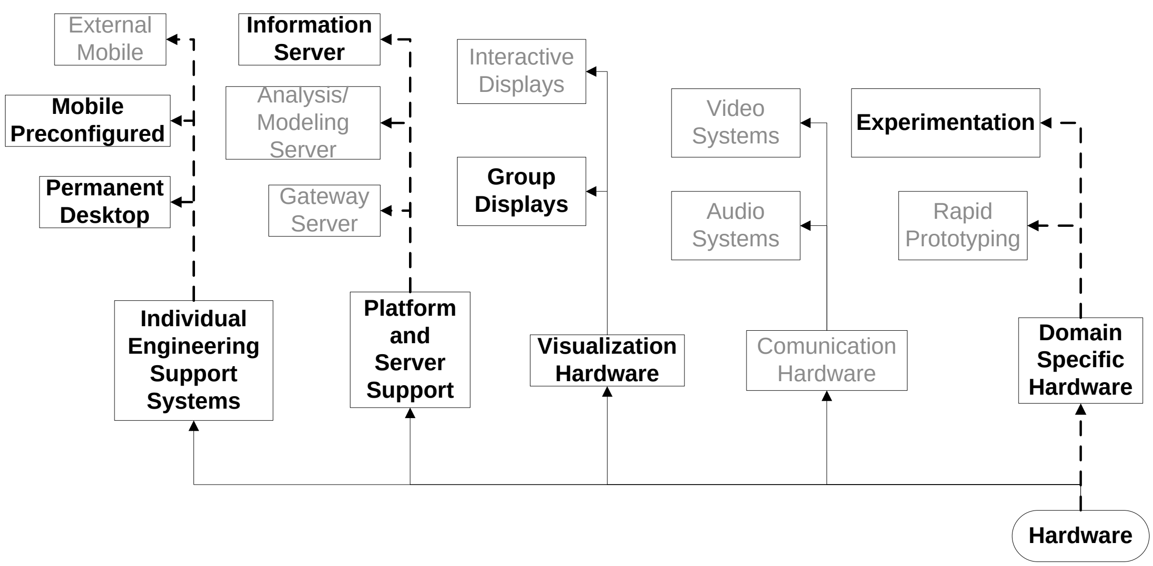

Figure 26: SRDC Hardware Configuration

SRDC Software

GENSAT is one of the design tools used in the Spacecraft Design Laboratory, it is a general purpose software application for satellite design. Multiple software packages for mission cost estimation exist; Excel is used to combine the estimation packages which are leveraged from previous designs [58].

The Satellite Toolkit (STK) used by SRDC is developed by AGI and is used to solve location and inter-visibility problems associated with land, sea, air, and space operations. This software is also used for guidance and the integration of multiple sensors in a system [64]. A table of domain specific software is listed below in Table 6.

Table 6: SRDC Domain Specific Software

Function	Tool Used
Orbital/Flight Analysis	Satellite Toolkit (STK)
Finite Element Analysis	Nastran, Ideas
Mathematical Analysis	Matlab/Simulink
Satellite Design	GENSAT
Programmatic	MS-Project

The software configuration found in the SRDC is located below in Figure 27.

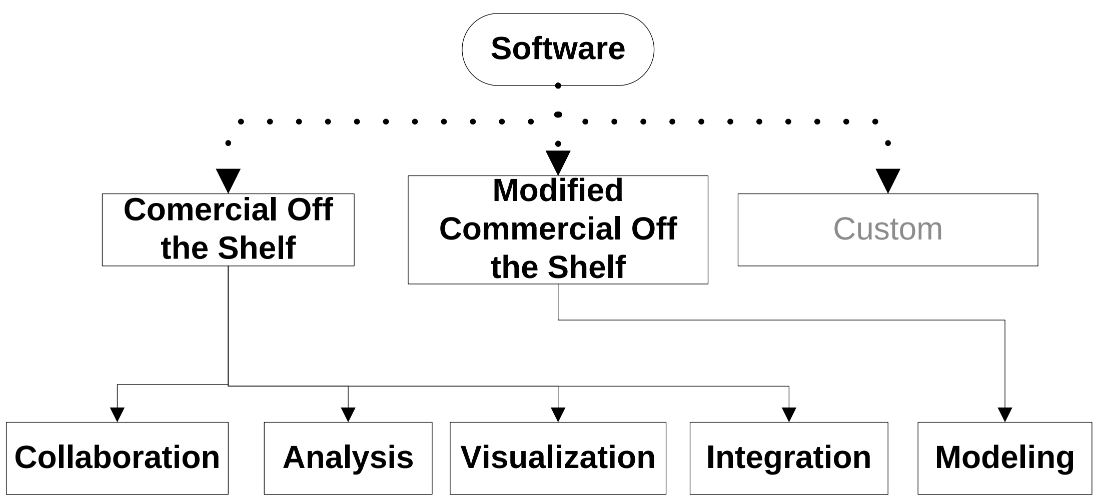

Figure 27: SRDC Software Configuration

SRDC Peopleware

The SDC consists of 9 designer workstations and one project manager workstation. The workstations are arranged around the room facing the wall and the project manager's workstation is located in the center of the room and is used to operate the projector. Each station represents one of nine subsystems commonly considered in the design projects at SRDC: orbit/propulsion/launch, payload, cost, thermal, communications/TT&C, power, systems, ADACS, configuration/structures [34]. The initial, notional layout of the SDC is shown in Figure 28.

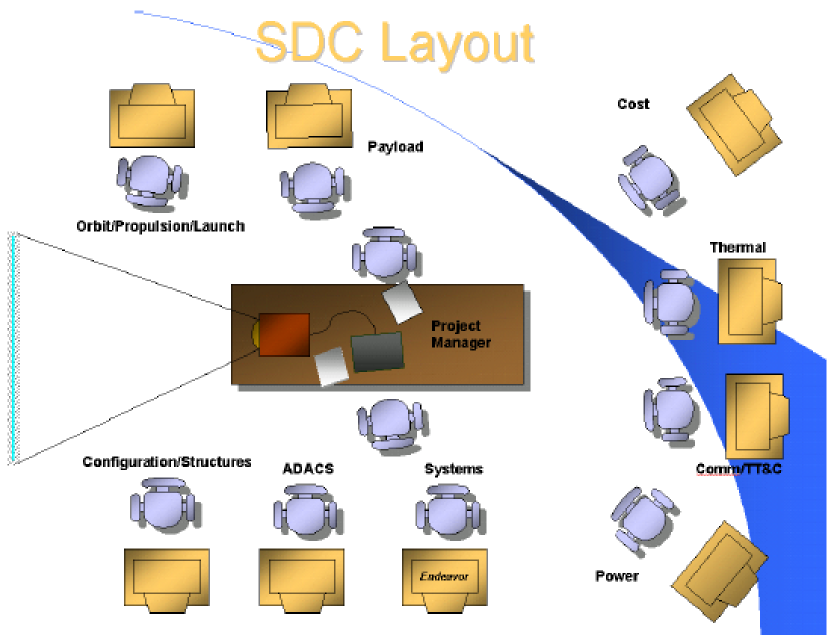

Figure 28: Spacecraft Design Center Notional Layout [24]

The SRDC utilizes software adapted to their purposes from the Aerospace Corporations Concurrent Design Center (CDC). All of the workstations link to the

Endeavor server which operates the CDC software. Each of the subsystems as a separate excel workbook which they control and is used to feed information to Endeavor which then outputs a read only systems workbook displaying all of the systems design information real time.

In order for a successful design session to occur at the SDC, preparation is necessary. The project manager and the systems engineer work together to define the requirements and bounds of each subsystem, which are distributed to the individuals prior to the session. This allows the subsystem designers to work independently of each other, if desired, on their own subsystem, but they cannot gain access to the read only systems information unless the systems engineer is present.

During a design session, the systems engineer has control of all of the data and is responsible for the total system design. The session is under control of the project manager and can be stopped and restarted at any time. The system engineer controls the design and is charged with integrating the subsystems and indicating to team members if the design begins to stray from the design envelope [24].

Only the configuration/structures engineer has access to SolidWorks solid modeling computer aided design software for licensing and cost reasons [24]. The CAD software is not integrated into the SRDC modeling software so configuration/structures subsystem workbook requires manual inputs to pull the data out of the solid model and into the SRDC software. A picture of a session in progress is shown in Figure 29.

Figure 29: Design Session at SRDC

The following figure describes the peopleware configuration at the SRDC, Figure 30.

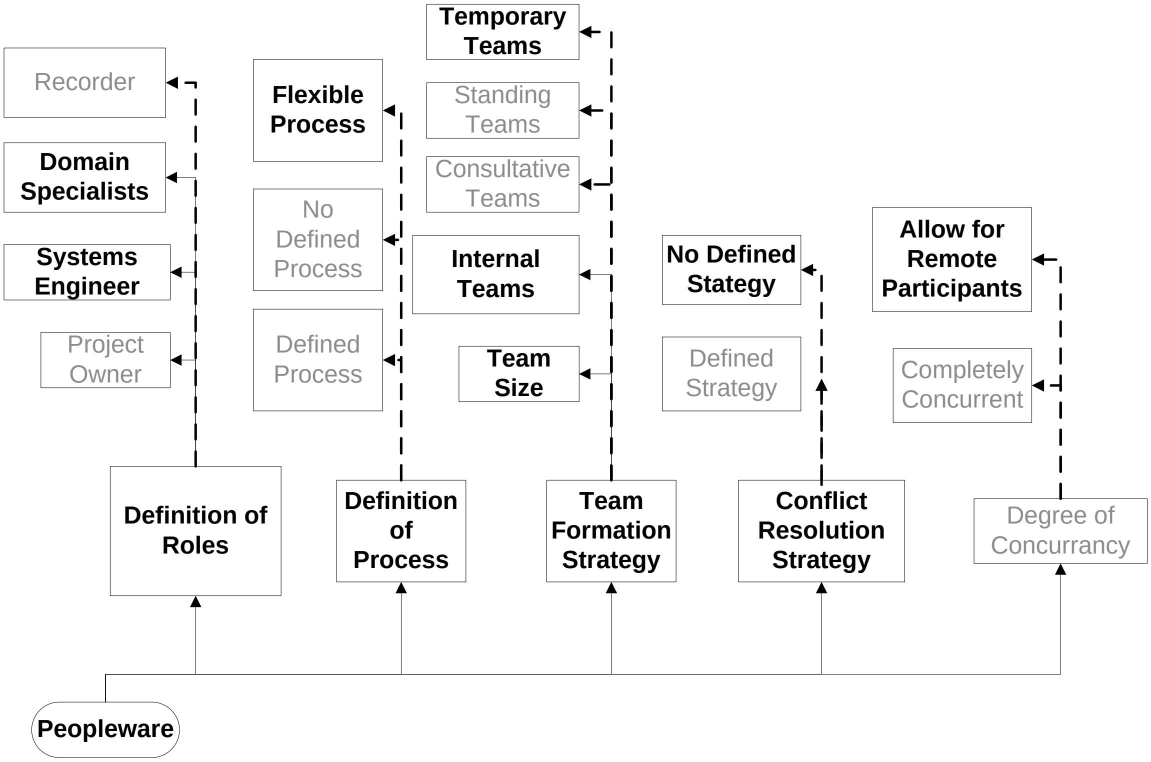

Figure 30: SRDC Peopleware Configuration

Concurrent Design Facility (CDF) at European Space Agency:

The Concurrent Design Facility (CDF) was established at the European Space Agency (ESA) in November of 1998, initially to study the role of the ionosphere as it pertains to the Sun-Earth relationship. After the first few missions a general studies program was conducted which investigated the role of concurrent engineering in mission design and planning [6]. The CDF is primarily used to conduct Phase-0 technical and financial feasibility studies for future space missions. Also, some payload instrument designs are conducted, reviews of Phase-1 designs, and education/training sessions are conducted as secondary thrusts [6]. An image of the CDF in session is shown below in Figure 31.

Figure 31: CDF in Session [6]

CDF Hardware

The main design room at the CDF consists of 30 design stations for general or specified use. Every two workstations share a monitor to display design information relevant to both designers or bring information posted on one of the 4 LCD display screens or the 6 X 2 meter projection screen closer. The main room also has one 16:9 smart board which allows for more intimate interaction with design information through the touch screen and the ability to take notes to an easily distributable medium. Each of the design stations have integrated microphones and web cameras for the inclusion of offsite designers and give ESA the ability to record their design sessions [60].

The CDF at ESA also includes a project design room which could be described as a breakout room. This room does not have any computer workstations but does allow for viewing of the Main design room and the design through 3 plasma screens. Another smartboard with PC support is included in the space to facilitate breakout design activities [6].

The CDF also shares the cost of a Stratasys Vantage rapid prototyping machine with another division at ESA. The machine uses Fused Deposition Modeling which utilizes plastic layers with a minimum thickness of 0.178 mm built up to the final shape of the model. This allows the designs at CDF to rapidly build scale models of concepts for evaluation [50].

The CDF hardware configuration can be found in Figure 32.

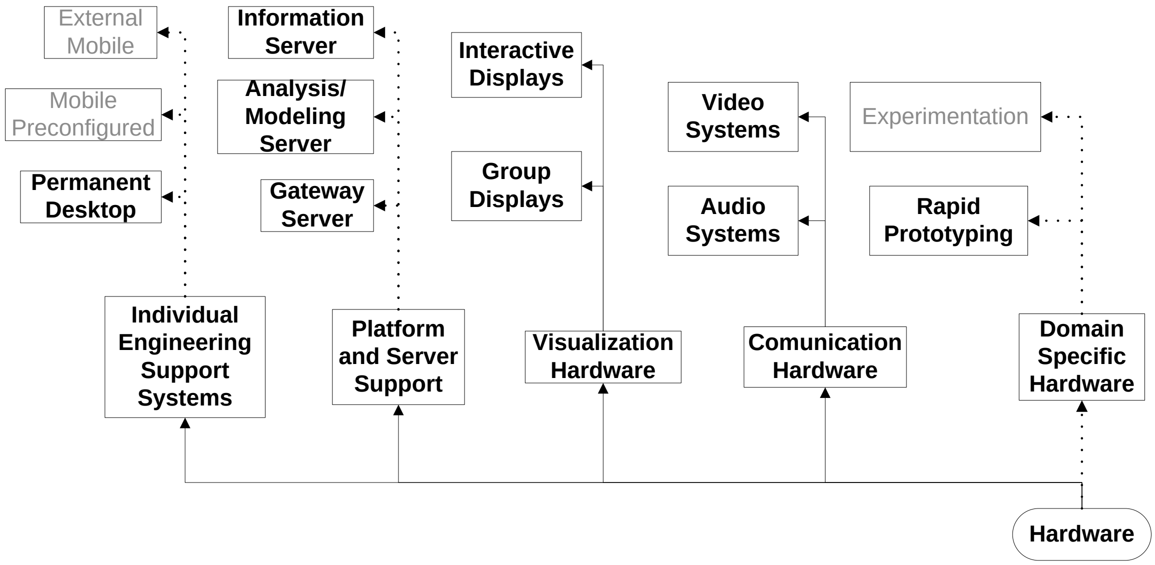

Figure 32: CDF Hardware Configuration

CDF Software

When choosing software for the CDF, COTS products were chosen to save time and money on development and support. Six key functions were identified for fulfillment by domain independent software: document storage & archive, electronic communication within the team, storage area for all data files, system modeling, project documentation, and remote audio/visual communication. Table 7, shown below, indicates the COTS software chosen for each function [19].

Table 7: CDF Software

Function	Tools Used
document storage & archive	LotusNotes database
electronic communication within the team	LotusNotes mail
storage area for all data files	NT file server
system modeling	Excel spreadsheets
project documentation	MS-Word
remote audio/visual communication	Video conferencing & Net meeting

Domain specific software was largely chosen based on what ESA had available to them already, in an effort to keep standard programs for each functionality across the entire company. The functions identified as required for the CDF are: Structural Design, Configuration, & Accommodation; Attitude & Orbit Control; Mission Analysis, Mission Simulation & Visualization; Programmatic; Cost Modeling and Estimation. Table 8 shown below, indicates the COTS software chosen for each function.

Table 8: CDF Domain Specific Software

Function	Tool Used
Structural Design, Configuration, & Accommodation	CATIA
Attitude & Orbit Control	Matrix X
Mission Analysis	IMAT
Mission Simulation & Visualization	EUROSIM
Programmatic	MS-Project
Cost Modeling and Estimation	ECOM Cost/Technical Database & Small Satellite Cost Model

The software configuration at the CDF is shown below in

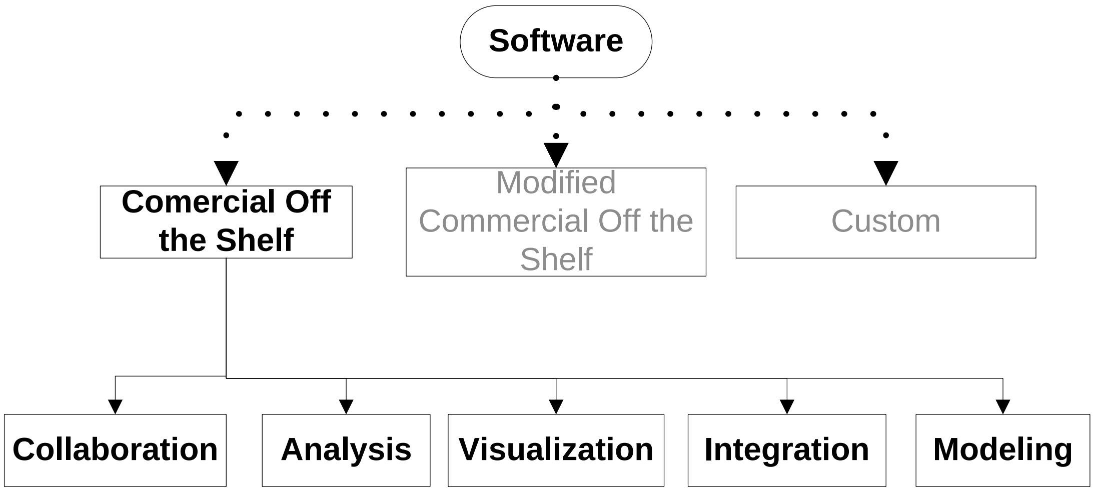

Figure 33: Software Configuration

CDF Peopleware

The CDF aims at creating a multidisciplinary design environment fostering effective communication, data interchange and engineering tools for a number of team members working concurrently. The facility consists of a central foyer surrounded by three design rooms and additional support rooms; a floor plan of the CDF in shown in Figure 34.

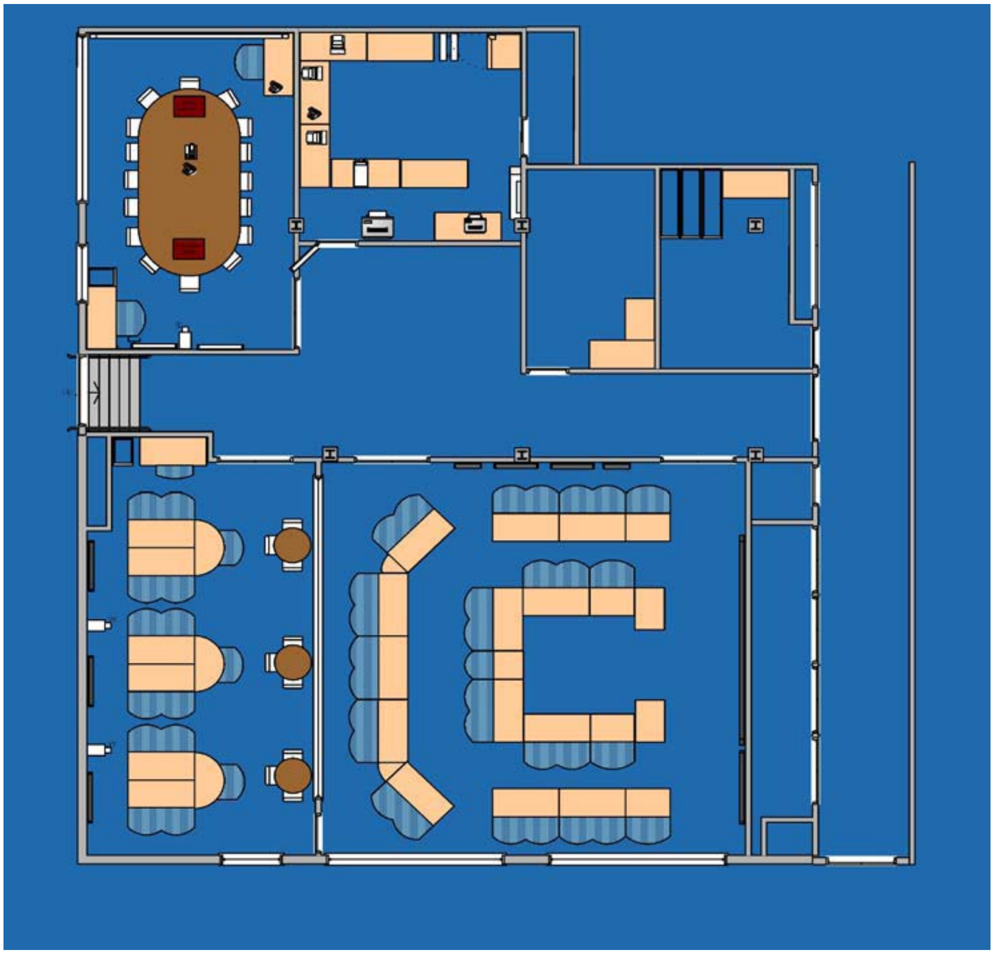

Figure 34: CDF Floor Plan[17]

The design team commonly assembled by ESA consists of 19 separate domain specific categories. They are: Team Leader, Systems Engineering, Missions Analysis, Ground Systems and Operations, Programmatic and Assembly Integration and Verification (AIV), Technical Risk Assessment, Cost Analysis, Simulation, Configuration, Structural Engineering, Attitude and Orbit Control, Propulsion, Communications, Data Handling, Power, Thermal Control, Mechanisms and

[17] http://www.esa.int/SPECIALS/CDF/

Pyrotechnics, Instruments, and a Technical Author. Each of these design functions is handled by one or more team members. A figure showing the location of each discipline and workstation is shown in Figure 35.

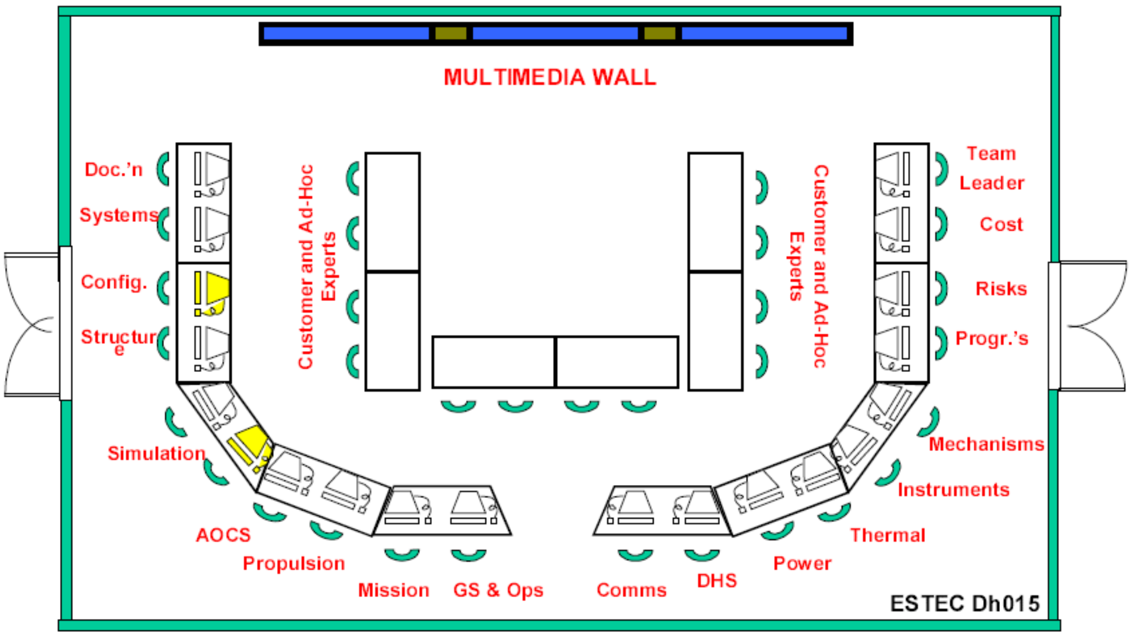

Figure 35: CDF Location of Domain Specific Team Members [23]

The Team Leader is responsible of the overarching management of the study, from setting up the team of experts required to compiling the final report with the technical author. The Team Leader mostly relies on the talent within ESA but can pull experts in from other organizations. All of the other team members support the team leader and focus on the quickest path available to converge the design and the mission objectives prior to the concurrent engineering sessions with the customer [23]. A list of the technical disciplines present at each design is shown in Figure 36.

POSITION
Systems
Instruments
Mission analysis
Propulsion
Attitude and Orbit Control
Structures/Configuration
Mechanisms/Pyros
Thermal Control
Electrical Power
Command and Data Handling
Communications
Ground Systems and Operations
Simulation
Cost Analysis
Risk Assessment
Programmatics

Figure 36: CDF Technical Disciplines [19]

During a design session, each domain can voice their opinions or findings to the rest of the team via an integrated microphone system at each workstation. Each workstation also allows the user to push their screen to the large team screen in the front of the room or to pull that screen down for closer inspection. All of the workstations have exactly the same PC with the exception of the configurations, simulation, and structures positions; they have custom designed PCs with domain specific software [19]. The CDF allows for remote sessions with JPL's PDC but requires concurrent operation of sessions.

The peopleware configuration can be seen in Figure 37.

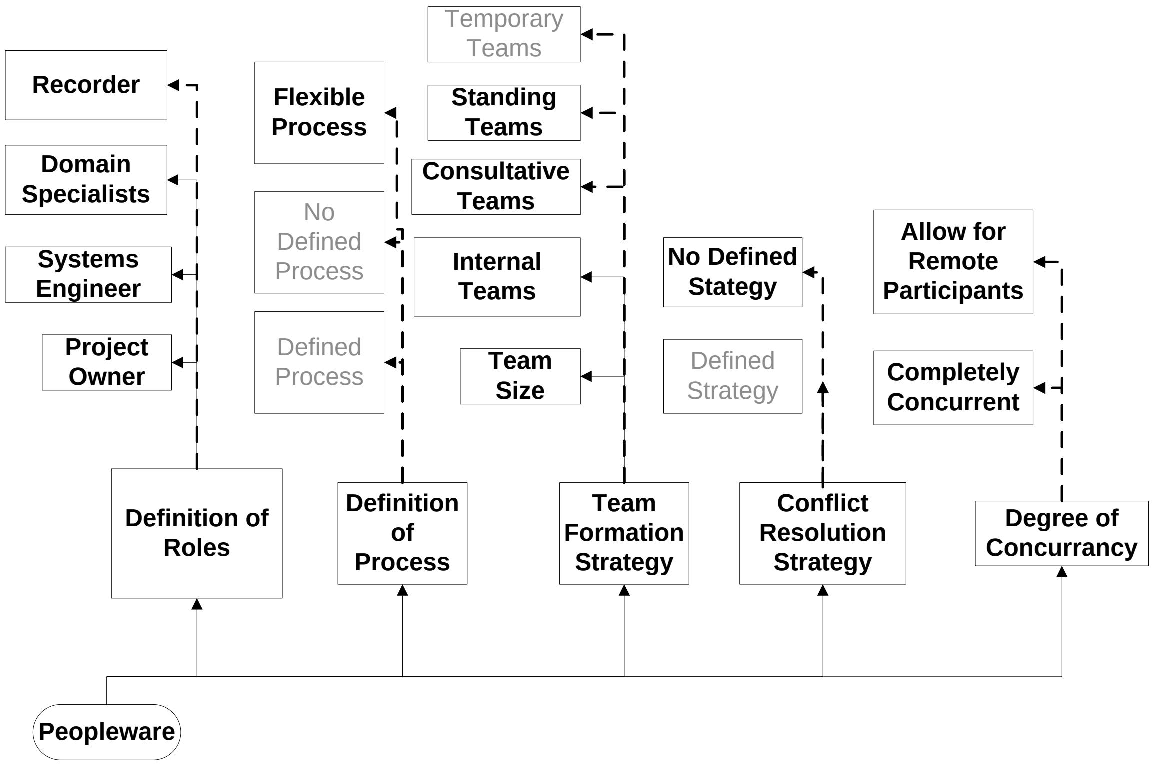

Figure 37: CDF Peopleware Configuration

<u>Integrated Concept Design Facility (ICDF) at TRW</u>

Again, in order to accommodate the better, faster, cheaper mantra in the aerospace industry, TRW established the Integrated Concept Design Facility (ICDF). The ICDF is currently in use at TRW and is succeeding in both of the goals TRW had leading up to the establishment of the environment: shorter lead times for conceptual designs and improved design quality [37].

ICDF Hardware

The main design facility consists of 15 workstations with desktop PCs. Each PC has one display and is linked through a central TRW server allowing engineers to work during “off periods”. There are two forward projected screens which are controlled by the team leader and can display any of the workstation's displays. There are two whiteboards/storyboards in the main design area for all sketching and mission planning during the design sessions. A copier and repository of previous design files are available in an adjacent room for ease of access. The center also has two breakout areas, one has a whiteboard and conference table, the other is standing room only [37].

The hardware configuration at ICDF is located below in Figure 38.

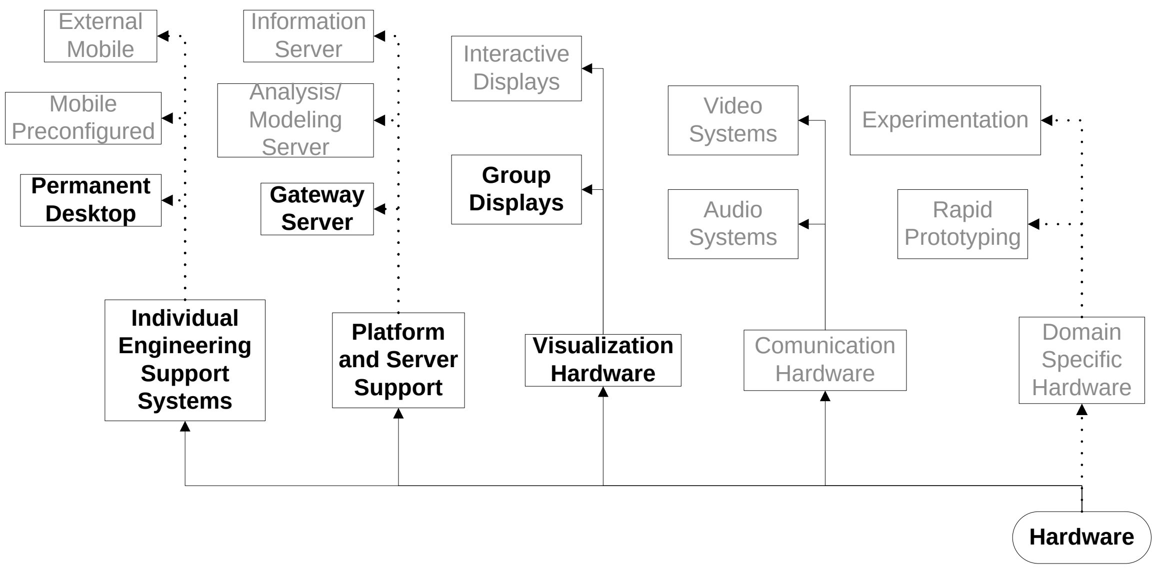

Figure 38: ICDF Hardware Configuration

ICDF Software

When choosing software for the ICDF mostly COTS products were chosen to save time and money on development and support. MS Excel is used for cost estimation and MS Word is used for documentation and dissemination of design information. Domain specific software used at TRW's design center is COTS software with custom integration interface. The custom interfaces guide the designer to the appropriate tools based on the objective they are attempting to accomplish. The domain specific is listed in **Table 10 [37]**.

Table 9: ICDF Domain Specific Software

Function	Tool Used
Structural Design, Configuration, & Accommodation	CATIA
Attitude & Orbit Control	Matrix X
Mission Analysis	IMAT
Mission Simulation & Visualization	EUROSIM
Programmatic	MS-Project
Cost Modeling and Estimation	ECOM Cost/Technical Database & Small Satellite Cost Model

The ICDF software configuration is shown below in Figure 39.

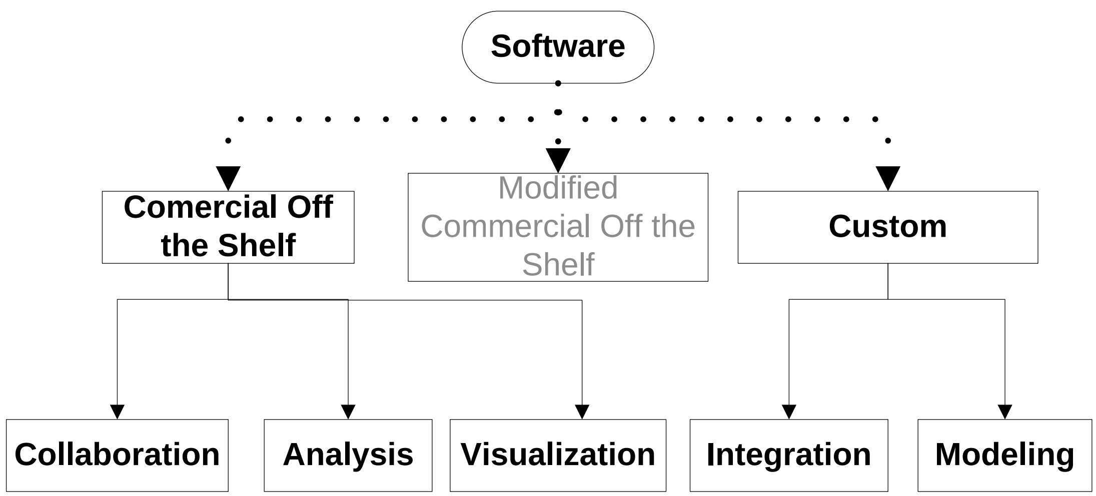

Figure 39: ICDF Software Configuration

ICDF Peopleware

The ICDF system engineers have chosen to follow a detailed script for each session. The process starts with customer needs definition which flows into the requirements. The team is then assembled by the system engineer and the requirements are then reviewed as a team. The team then determines the top level architecture which defines the overall design space. The design components are then sized and iterated by the subsystem domain experts. The overall design is documented and presented to the customer prior to dispersing the team so any changes that are required can be made [37].

Along with the process the individual roles and responsibilities are documented and explained prior to starting the requirements review. The facilitators serves one half the function of the systems engineer and keeps the meeting moving and on schedule, while a technical lead monitors technical progress and keeps the requirements in check, the second half. Subsystem engineers are responsible for their system and coordinating the subsystems design recommendations to the team. A dedicated pricing specialist is used to develop the system cost. A systems manager and database manager are responsible for avoiding conflicts between subsystems and format. The project managers participate in the session throughout the process as a customer or representing an external customer [37].

The facility includes a host of different features to support a concurrent engineering session. The 15 workstations are arranged in a U-shape around a standing room only conference table. Two projection screens are located at the front of the room. Two storyboard walls are used for mission planning and definition. A lunch and coffee table is located at the rear of the room to allow for caffeination and sustainment of the team. A library of previous designs and reference materials are located in an adjacent room along with the copier. Two breakout rooms are available during the session. One is setup only for discussions as it is an empty area. The other has a conference table and a whiteboard for sidebar discussions. The facility layout can be seen in Figure 40 [37].

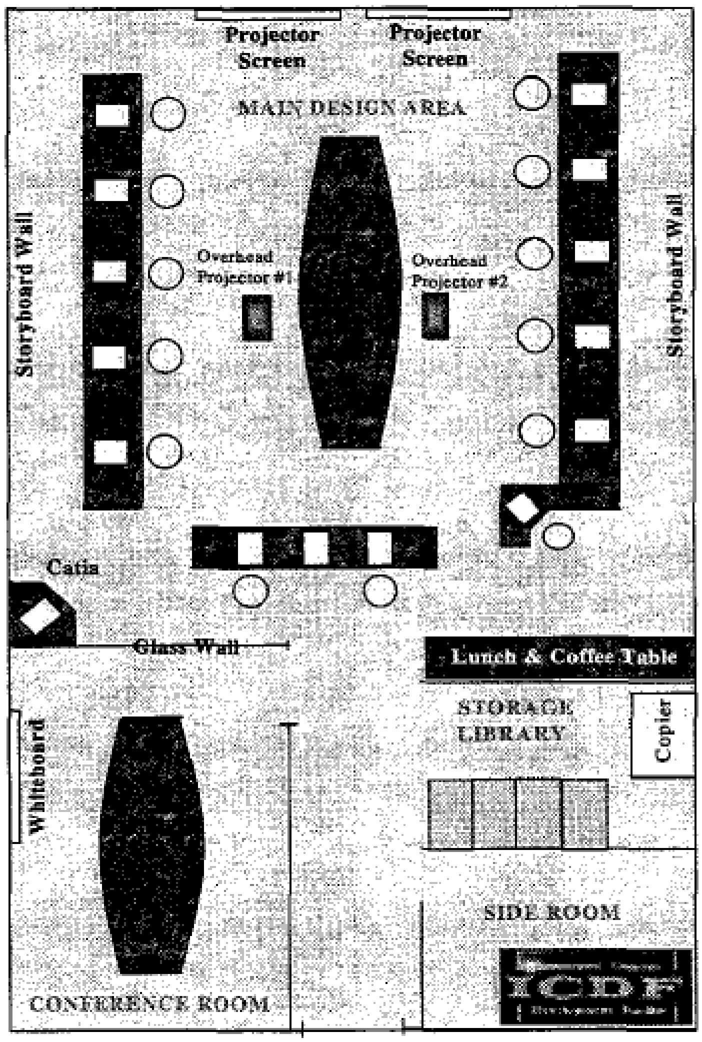

Figure 40: ICDF Facility Layout [37]

The ICDF peopleware configuration can be found in Figure 41.

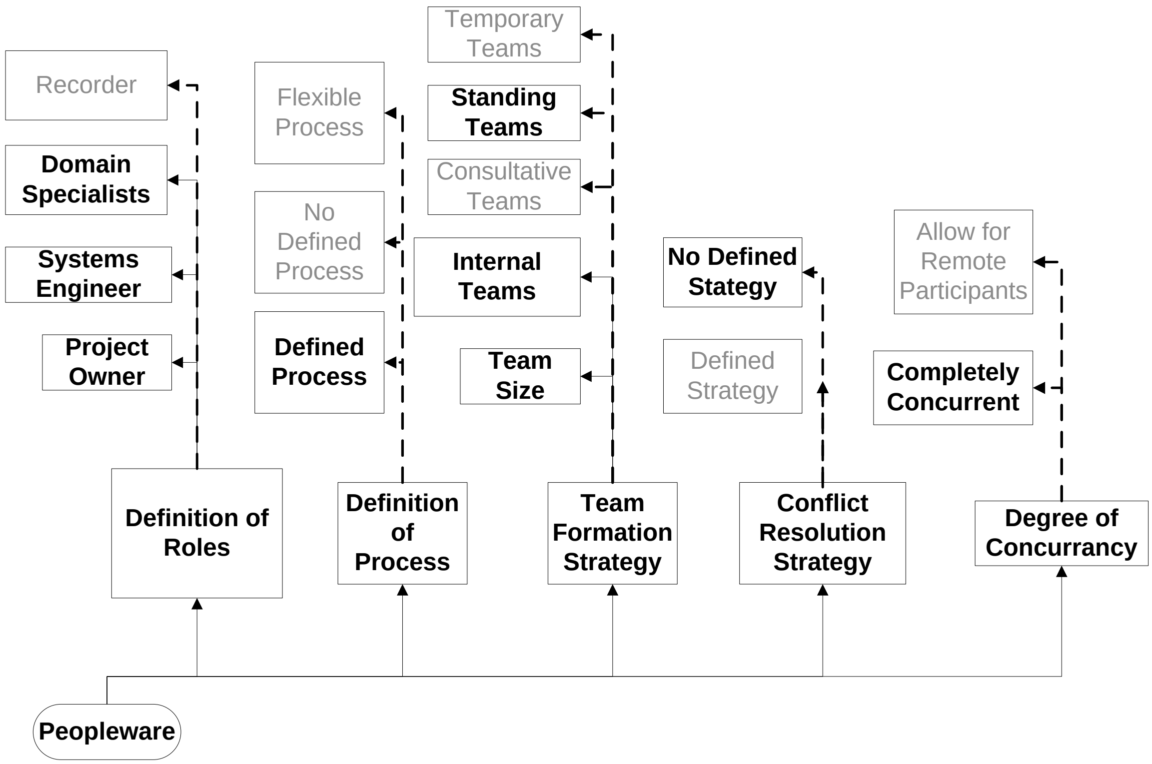

Figure 41: ICDF Peopleware Configuration

<u>Space Systems Analysis Laboratory (SSAL) Concurrent Engineering Facility at Utah State University</u>

Utah has a growing interest in space system design and has, for two reasons, established a concurrent engineering environment. The first and foremost is to augment the existing space research teachings at the university. The second is to perform system level designs on space systems. They chose the PDC and CDC as models for development of an in house center and intend to team with other centers to test distributed concurrent design in the near future. A layout of the facility can be seen in Figure 42 [26].

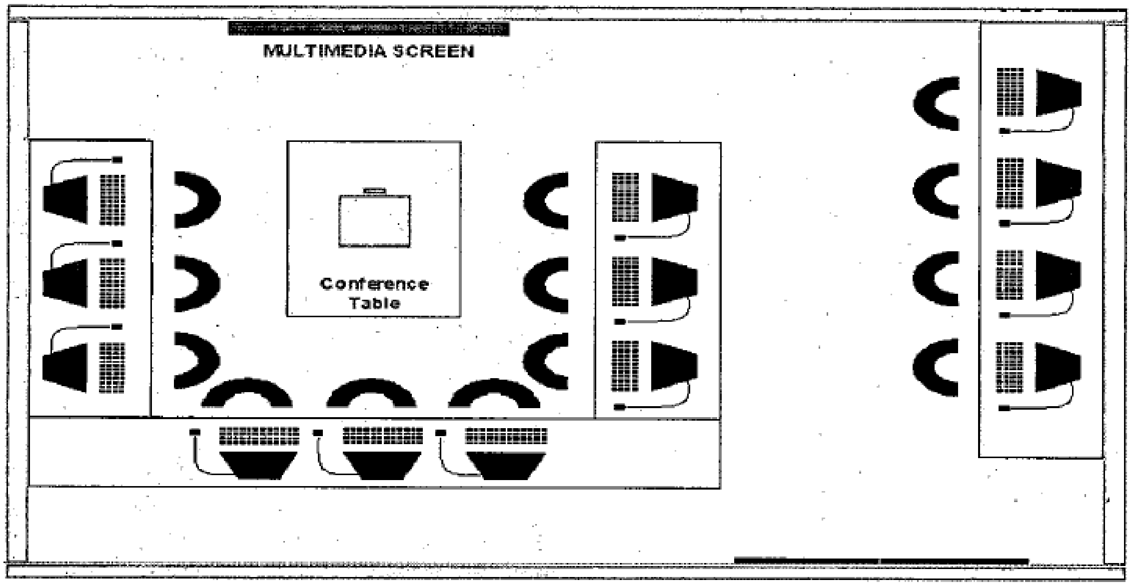

Figure 42: SSAL Layout

SSAL Hardware:

The SSAL facility at Utah State has 9 workstations set up in a U-shape with 4 additional workstations setup outside of the U against a wall. There is one projector with a single group display which is located to the rear of the room, requiring participants to turn around to see the display. No audio, video, or phone systems are located in the room as this is predominantly a teaching facility. The computers are linked together via a dedicated server and can be linked to the universities network [26].

The hardware configuration for the SSAL facility can be found in Figure 43.

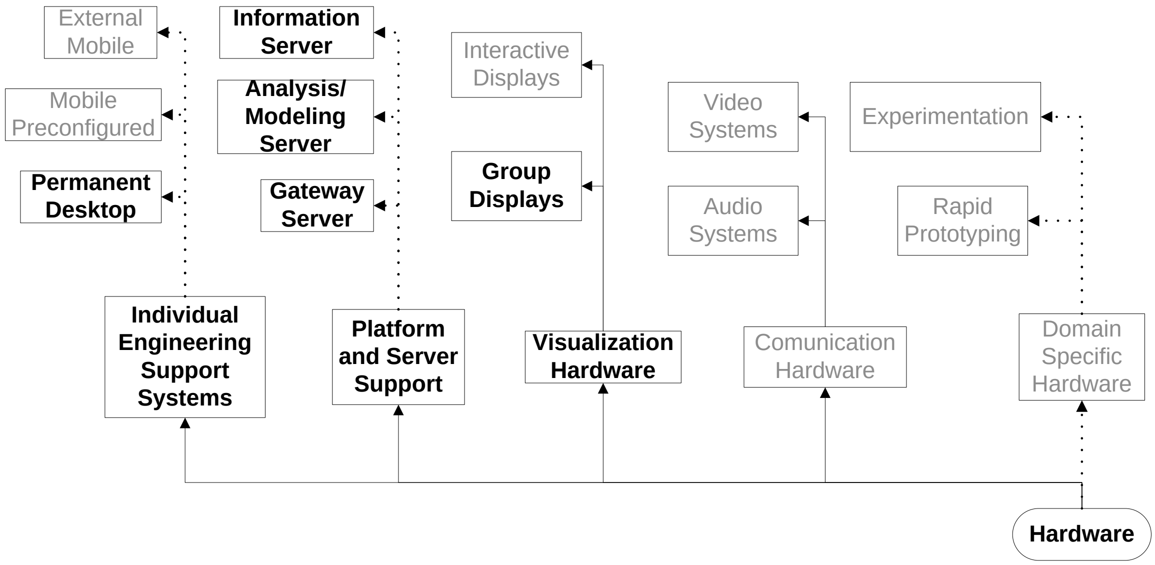

Figure 43: SSAL Hardware Configuration

SSAL Software:

The software installed on the PCs is commercial of the shelf items ranging from the common Microsoft Office Suite to the specialized Satellite Tool Kit. Utah State University chose to use MS Excel to establish and model the system. All of their designers had previous exposure to MS Excel and the concurrent engineering environments that the SSAL was modeled after used MS Excel based system models. Solid Edge and Ideas were chosen as the visualization software because they are the platforms that the university teaches to their students. The SSAL uses Matlab for analysis and simulation. A list of specialized software used by function is listed in Table 10 [26].

Table 10: SSAL Domain Specific Hardware [26]

Function	Software
Flight Control	Satellite Tool Kit, SWINGBY, GTDS,GMAN, MAnE, Custom Target Acquisition Tool, Freeflyer Engineer, Solar Cycle
Power	Electronic Power Spacecraft Simulation Tool, Solar Power Modeling Tools, Orbit Dynamics Energy Balance Too, Battery Sizing Tool, Voltage Trade Sheet, Radiator Degradation Tool
Communications	CLASS

There is numerous domain specific software tools used at the SSAL, more than other centers. That is mainly for teaching purposes, to expose the students to a broad array of tools used in industry. The software configuration found in the SSAL is shown below in Figure 44.

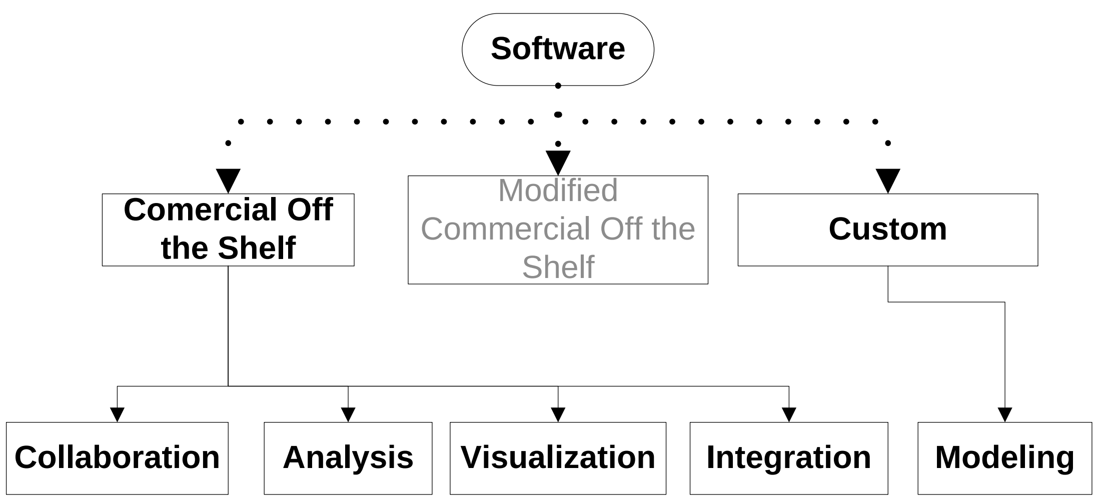

Figure 44: SSAL Software Configuration

SSAL Peopleware:

The SSAL serves the aerospace industry exclusively and users include students as the designers. By focusing on education SSAL has established an environment that will support a semester long design and facilitate lectures as well as design sessions. Designers, students, are introduced to all aspects of the concurrent engineering environment process, technical, cost and schedule. The focus remains on the aerospace industry so a wide range of domain specific tools are introduce realizing that the students will disperse to numerous companies where any of these tools could be used [26].

During a session the team leader, the professor, controls the rear group display screen and moderates the session. Any of the nine computers can be displayed on the screen at the leader's discretion. The domain experts rotate throughout the semester long process to expose the students to all of the design center activities. Students can work offline to progress their assignments and the integration occurs real time in session. The SSAL utilizes subsystem excel data sheets linked together to form the full systems model. No video recording or audio recording is available in the center, nor is the ability for designers to work remotely in session, the classes require physical attendance [26].

The peopleware configuration can be found in Figure 45.

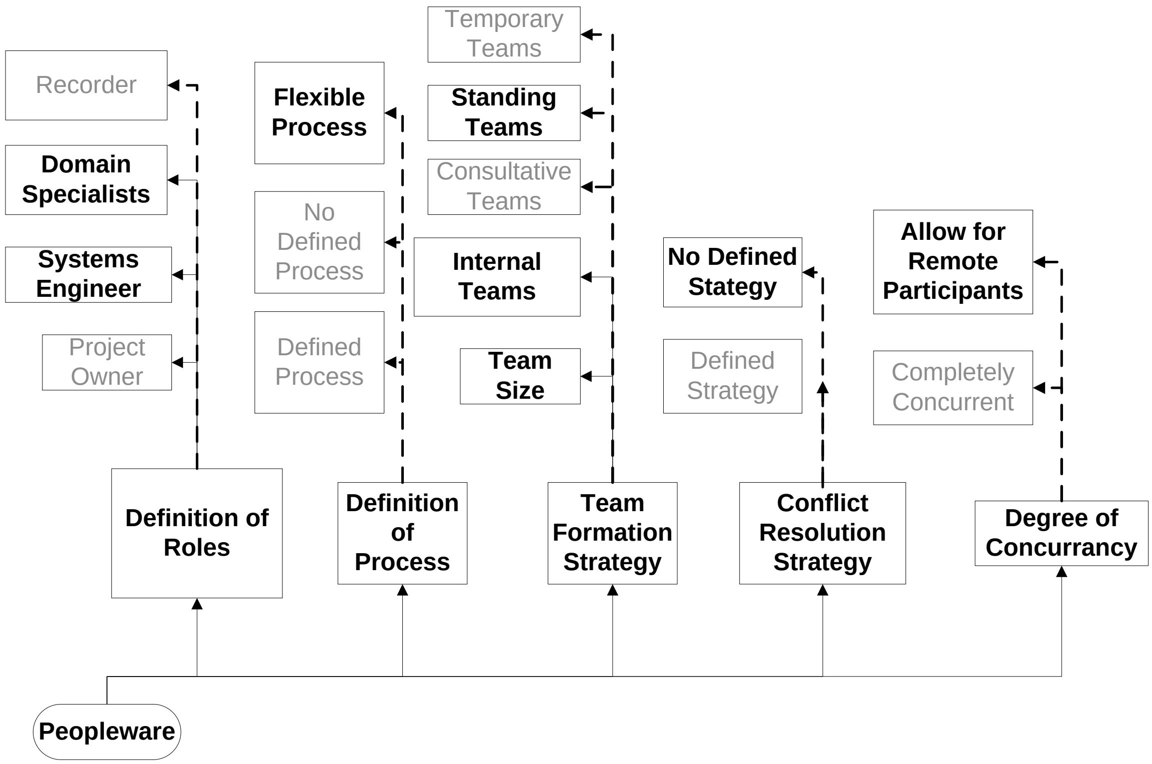

Figure 45: SSAL Peopleware Configuration

Integrated Missions Design Center (IMDC) at NASA Goddard Space Flight Center

During the mid 1990's when NASA's money and labor pool was shrinking, the Integrated Missions Design Center (IMDC) was established at the Goddard Space Flight Center (GSFC) in an effort to improve efficiencies. The old design process was handled by temporary, adhoc teams that did not communicate well with each other throughout the design. Further, only one subsystem was designed at a time making it difficult to change items designed first and drawing the design process out needlessly [51].

Once established, the IMDC enabled GSFC to perform a concept study in one week as opposed to three months using the old techniques. This new rapid turnaround led to a paradigm shift at IMDC. The new IMDC paradigm is shown below in Figure 46 [51].

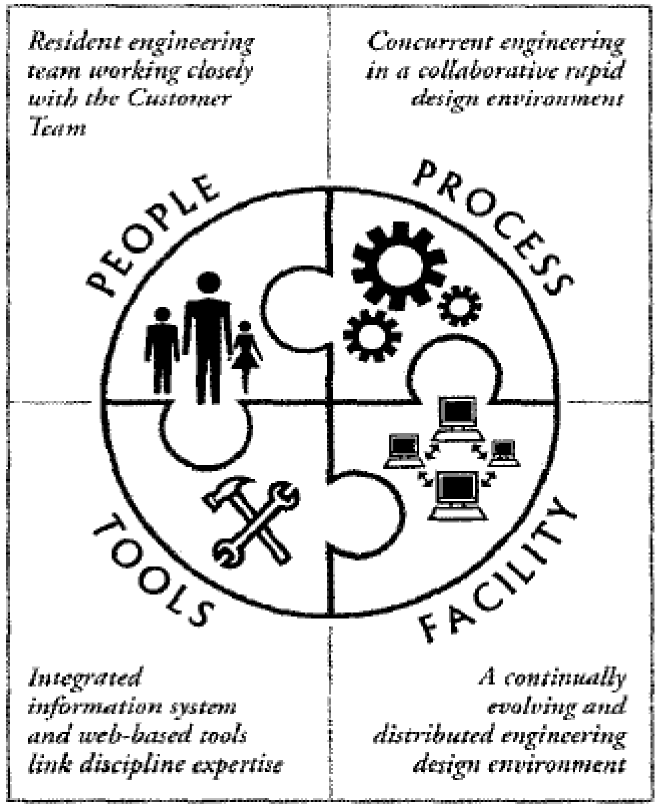

Figure 46: IMDC Center Paradigm [51]

IMDC Hardware

The IMDC has 20 individual engineering workstations consisting of a personal desktop computer, a single display, and a microphone. The computers are linked through a centralized server and allow access to outside facilities and colleagues via Ethernet connection. In the front of the room, three large displays engulf the wall, one of which lifts to allow access to an electronic whiteboard [51]. The hardware configuration is shown in Figure 47.

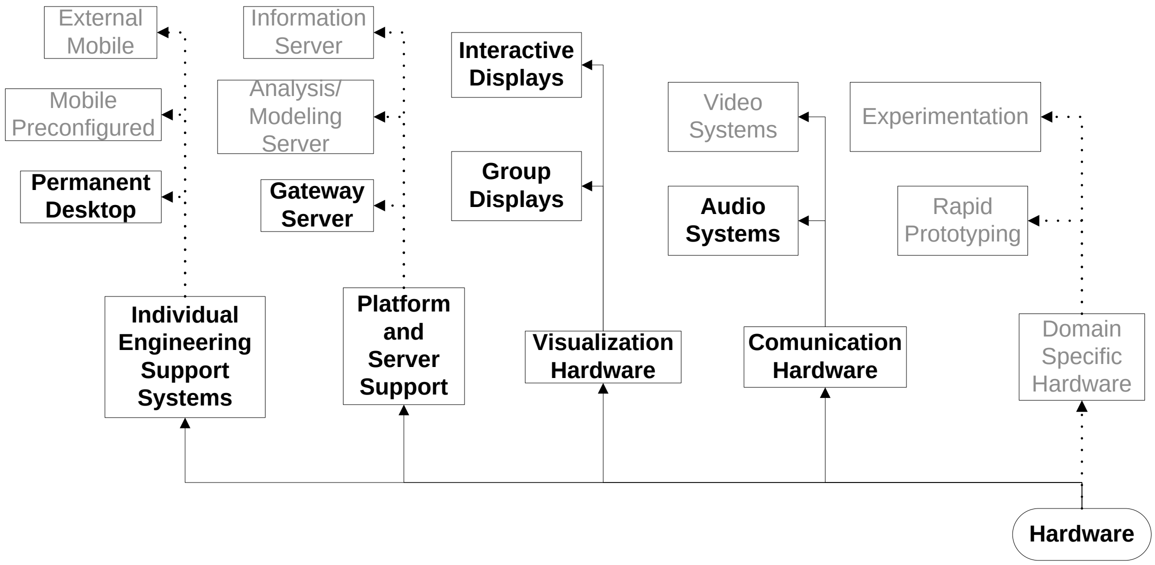

Figure 47: IMDC Hardware Configuration

IMDC Software

The IMDC facility makes use of a wide range of COTS, modified COTS and custom software tools. By maintaining a wide range of software tools, the engineers are able to accommodate a wide range of design problems. As usual the standard MS Office suites are loaded on the PCs within the center. A partial list of the supported tools can be seen in Table 11 [51].

Table 11: IMDC Domain Specific Tools

Function	Software
Flight Control	Satellite Tool Kit, SWINGBY, GTDS,GMAN, MAnE, Custom Target Acquisition Tool, Freeflyer Engineer, Solar Cycle
Power	Electronic Power Spacecraft Simulation Tool, Solar Power Modeling Tools, Orbit Dynamics Energy Balance Too, Battery Sizing Tool, Voltage Trade Sheet, Radiator Degradation Tool
Visualization	Autocad, Pro-E
Structural Analysis	Ideas, Pastran/Nastran, On-Line Launch Vehicle Selection Tools
Communications	CLASS
Pricing	PRICE-H

All of the tools are maintained by the sub-systems engineers who use them with little or no central support from IMDC [51]. The customizations are also maintained by the sub-system engineers. A software configuration can be seen in Figure 48.

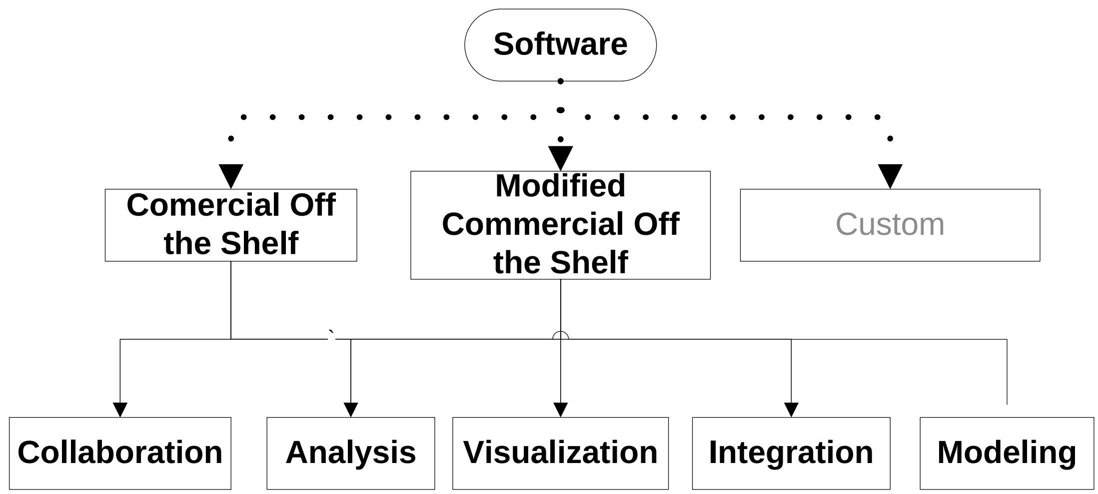

Figure 48: IMDC Software Configuration

IMDC Peopleware

The process used by the IMDC is very detailed and scripted. The client first completes an online support request form, identifying general information regarding mission type, scope, and time frame required. The form has roughly 100 entries and is intended to be all inclusive. This form is followed up by one or more pre-work meetings between the client and the systems engineer. All designs are desired to be completed in 4-5 days using the following script in Table 12 [51].

Table 12: IMDC Design Script [51]

Day	Process
Day 1, AM	Client brief to IMDC team on mission and science objectives and IMDC objectives. IMDC systems engineer briefs DET on pre-work results and engineering approach.
Day 1, PM	Coordination meeting with full IMDC DET and client team to review current baseline concepts, identify open issues, and schedule open splinter sessions. Client collaboration and mission design process.
Day 2-3, AM	Coordination meeting with IMDC and client teams mission design process continues
Day 2-3, PM	Coordination meeting with full IMDC DET and client team to review current baseline concepts, identify open issues, and schedule open splinter sessions. Client collaboration and mission design process.
Day 4, AM	IMDC DET completes final analysis, reviews final end-to-end conceptual design, prepares final presentation package for delivery to client
Day 4, PM	Final design study results presented to client team action items resulting from client briefings are reviewed and are dispositioned. A short debriefing is held with client. The team begins closeout of action items and finalizes documentation.

The design team used by IMDC includes a systems engineer, a technical lead, and 17 different domain specialists. The represented domains are listed in Table 13 [51].

Table 13: IMDC Domain Specialists [51]

Flight Dynamics and Attitude Control	Propulsion and Propellant
Command and Data Handling	Communications Systems and RF Links
Flight Software	Solar Array, Battery, and Power Electronics
Mechanical and Structures	Thermal Control
Mission Operations and Ground Systems	Launch Vehicle Capability
Reliability and Safety	Integration and Testing
Mission Cost Estimation	Mission Risk Analysis
Orbital Debris and Deorbit Analysis	Orbit Environment Assessment
Risk Management	

All of the specialists listed in Table 13 have a place in the IMDC environment. The environment is about 1000 square feet and has 20 workstations. There is one table used for collaboration with the customer. No group display hardware is incorporated into the center. The IMDC environment can be seen in Figure 49 [51] and a hardware configuration can be seen in Figure 50.

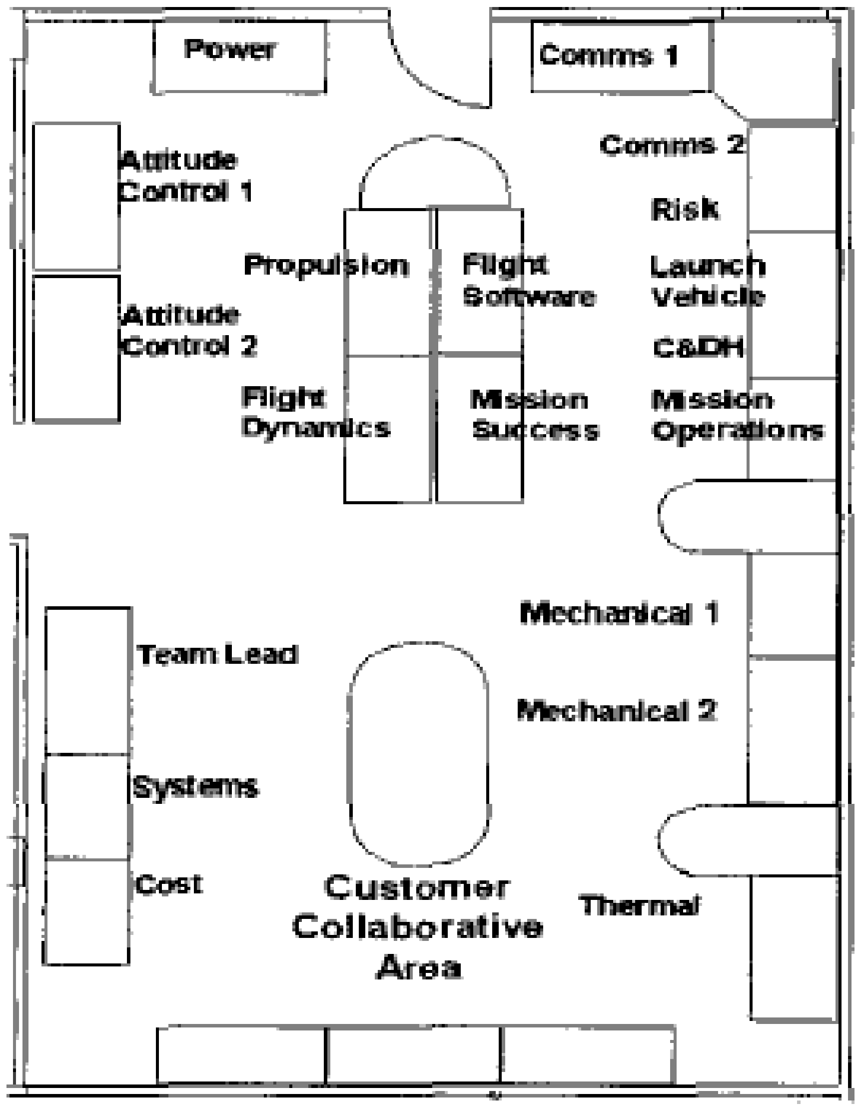

Figure 49: IMDC Facility Layout [51]

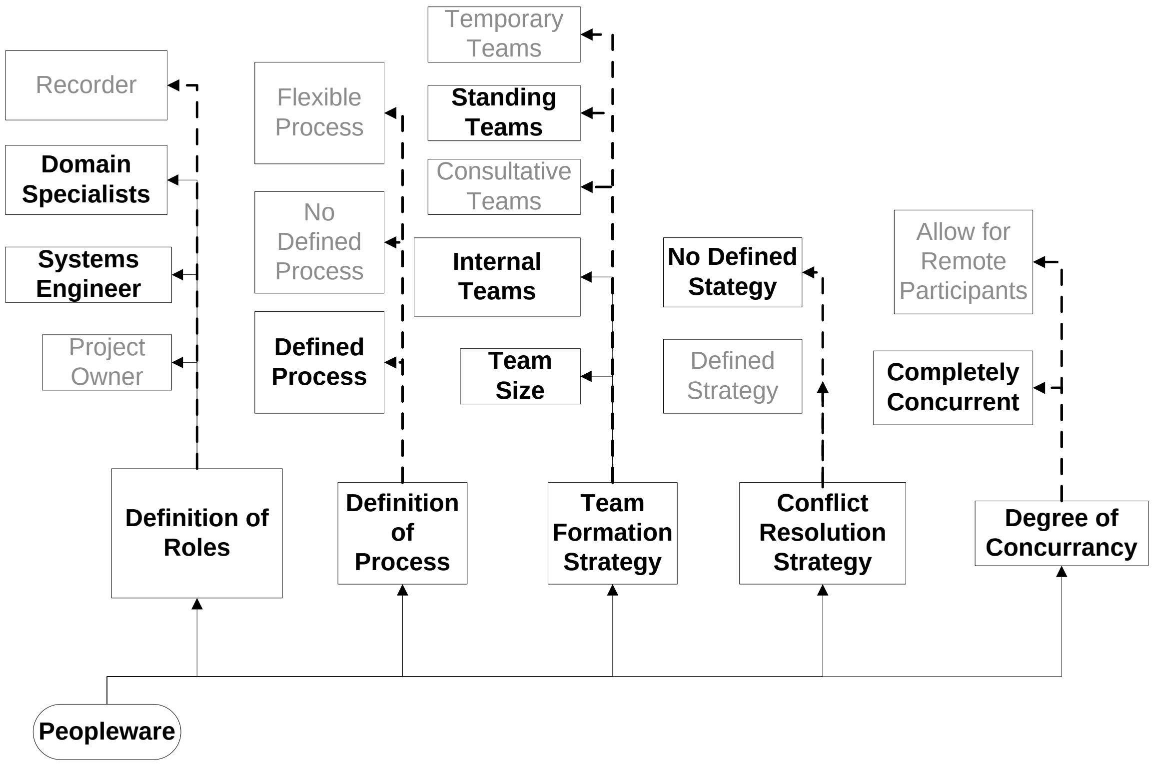

Figure 50: IMDC Hardware Configuration

<u>Space System Rapid Design Center at Ball Aerospace and Technologies Corporation</u>

The Space System Rapid Design Center (SSRDC) at Ball Aerospace and Technologies Corporation was developed to compete with the growing trend of concurrent engineering environments for aerospace applications. It is used to create rough cost models for an aerospace design using a virtual concurrent engineering environment. COTS tools and equipment were used to keep the cost and maintenance of the environment low [8].

SSRDC Hardware

The SSRDC is projected to only require one server to link together all of the remote team participants. It was desired to reduce the amount of equipment required to run a design session. A single 300 MHz server with 4GB of storage was all that was required for the prototype equipment [8].

SSRDC Software

The SSRDC makes use of custom internet, COTS and modified COTS software tools. Some of the most noteworthy software tools include those for requirements, collaboration, visualization, modeling, simulation, and customer interaction [8].

The custom internet tools are used to link together supplier information to aid in choosing available components and determining their cost. These tools were developed because linking to vendor information was cheaper and easier to update than a database of vendor information [8].

SSRDC uses collaboration tools to exchange data between team members, control access to tools and data, and manage work flow. They rely on AutoCad modified with a visual basic engine to allow automation from the system model. The system model is generated from excel sheets which are driven by DOORS, a requirements handling tool. Through flowcharts and other visual aids, requirements can be presented in an easy to follow manner. Other domain specific software tools are displayed below in Table 14 [8].

Table 14: SSRDC Domain Specific Software

Function	Software
Visualization	AutoCad with modified visual basic code.
Analysis	MathCad, Matlab, Math Connex
Communications	Livelink
Orbital/Flight Analysis	Satellite Tool Kit (STK)

SSRDC Peopleware

When the SSRDC was established, every attempt was made to pare down the resources required while obtaining similar results as other concurrent engineering environments. They recognized that in industry, having the correct person representing the required specialty at a particular point in time is difficult. Through the use of internet tools SSRDC attempts to host virtual/remote concurrent engineering environment sessions. They attempt to complete designs within 1-2 weeks of beginning the study. They recognize that they cannot focus too heavily on one particular type of design and remain competitive in industry so the tools and methodologies are meant to be flexible. A generalized process flow model can be seen in Figure 51 and a system model diagram is shown in Figure 52 [8].

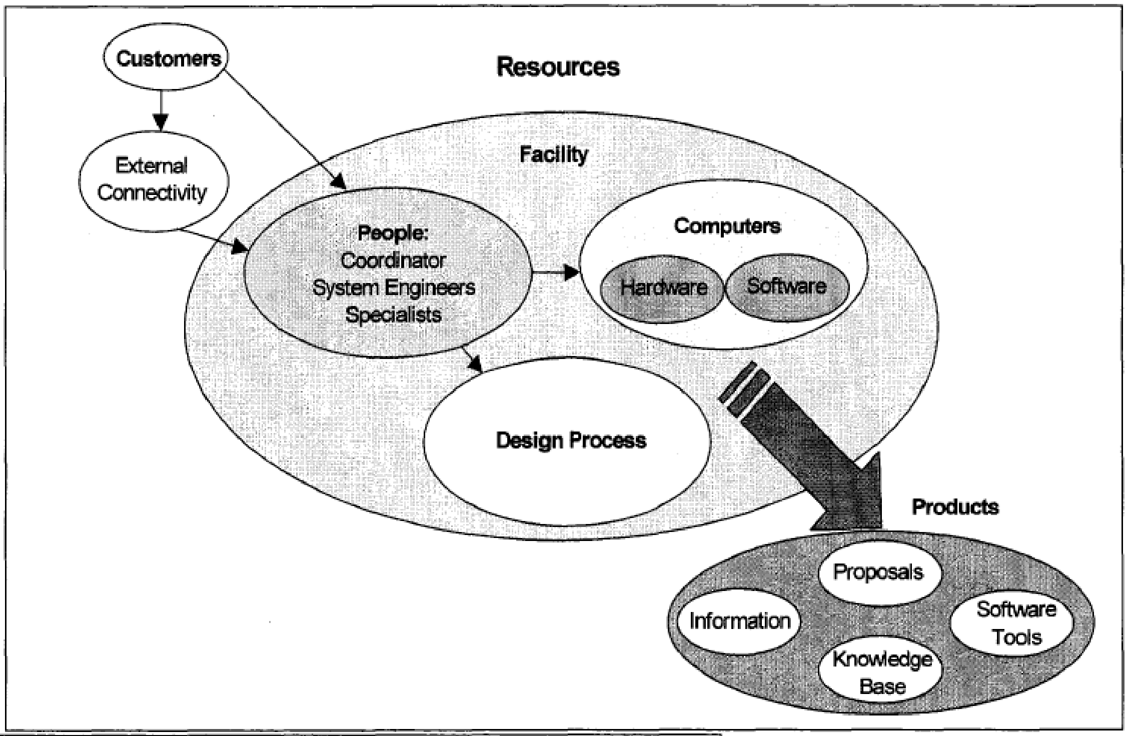

Figure 51: SSRDC Generalized Process [8]

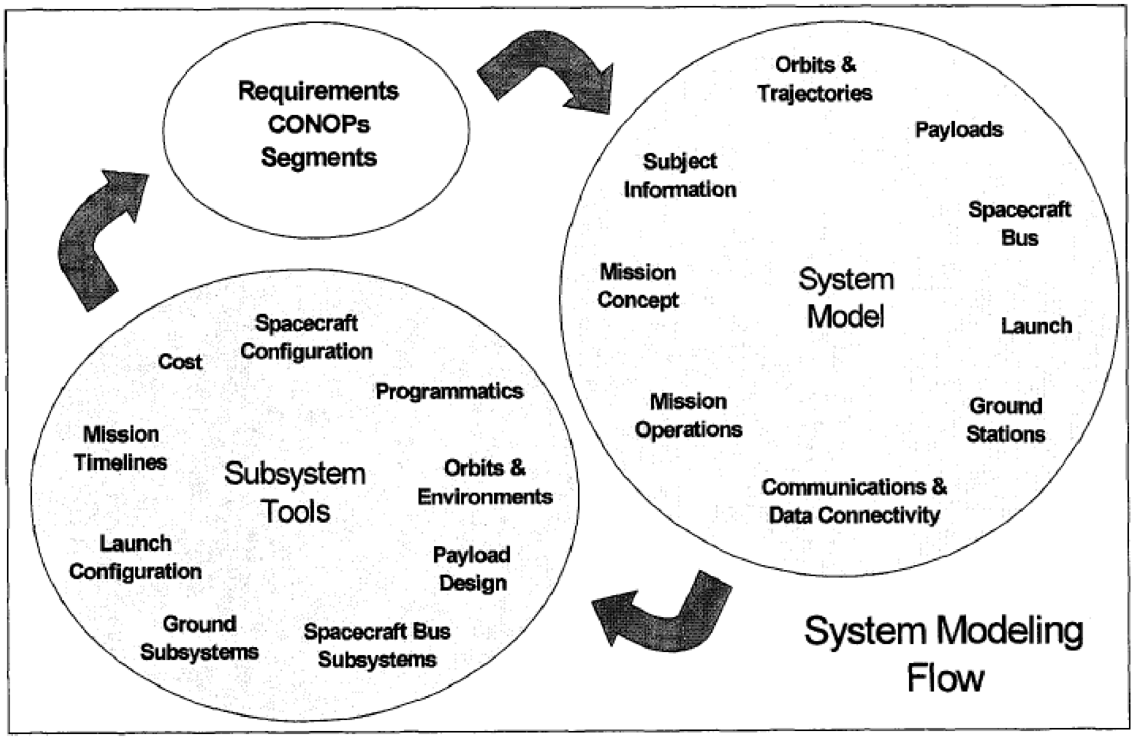

Figure 52: SSRDC Data Flow through a System Model [8]

This model is all hosted over internet tools and virtual communication. Limited information has been published regarding the success of the center. What has been published indicates that the virtual concurrent environment is successful at increasing quality by 40-50%, but the success enjoyed by JPL and CDC has not yet been achieved [8].

Satellite Design Office (SDO) at Dornier Satellitesysteme (DSS)

The Satellite Design Office (SDO) at Dornier Satellitesysteme (DSS) focuses on the concept design of satellite bus and payload systems. Their designs center around supporting the payload, delivering the payload at the correct temperature, providing electric power, controlling the instruments, collecting data, and providing storage.

SDO Software

The SDO has published limited information on the software used in their facility. The standard MS Office suites are used for communication and documentation. The system model is generated using MS Excel by linking subsystem design information to a master spreadsheet.

SDO Peopleware

The SDO has a very well defined process that is employed in satellite design. The team is lead by a systems engineer who interacts with the customer and develops the initial requirements documents. Prior to the design, session the team members are given the design requirements for review. The requirements are discussed and clarified at the beginning of the first design session. Each of the subsystems is represented by an engineer who develops the initial concept for their component. The system is then integrated using Excel and iterated until what is judged to be an adequate design is developed. Tradeoff studies are run at each review of the design to determine where mission parameters can be adjusted to accommodate mass, cost, etc. aspects of the design [61].

Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology

The Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology was developed in 1999 and is modeled after JPL's PDC. It currently houses three Macintosh and five PCs and is primarily used as a teaching tool. The LSMD uses self developed tools to teach students about concurrent engineering design over the course of a semester. Since the design is drawn out over the course of a long period of time, little has been required in the form of automation of the processes [25].

Space System Concept Center (S^2C^2) at Technical University of Munich

The Technical University of Munich has also developed a concurrent engineering environment as a teaching tool. Using approximately 10 user stations, the environment provides students with hands on exposure with tools and methodologies used in the aerospace industry. Excel based models are used to integrate the design and MuSSat is used to allow the students to design as he or she finds the time. This center is modeled after the Cal Tech LMSD [25].

Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT

Another teaching concurrent engineering environment can be found in the Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT. This center is 14 design stations and two projectors. PCs are not provided in the environment as each student receives a campus laptop upon entering the college. The facility is designed around two modes: design mode and teaching mode. No indication was given that this facility could support any other industry other than academia [25].

The Center at Boeing Military Aircraft Company

The Center at Boeing Military Aircraft Company was developed in 1999 to support the redesign of the C-17 for life extension. This environment was setup around determining which areas of the C-17 needed to be re-engineered. The center was modeled around the PDC. It houses 10 PCs and one projector. A customer can connect a laptop to the project for requirements briefings and design meetings [25].

Human Exploration and Development of Space Integrated Design Environment (HEDS-IDE) at Johnson Space Center

The Human Exploration and Development of Space Integrated Design Environment (HEDS-IDE) at Johnson Space Center opened in 1997 and is tasked with the human to Mars campaign. The center does not house standing teams and uses customized/specialized Situation-Base Design models generated by Lockheed Martin and the Human Mars Mission Modeler (HMMM). A method of costing has not yet been planned but is on the horizon for development [25].

Summary of Surveyed Concurrent Engineering Environments

The concurrent engineering environments surveyed show key similarities and key differences that will need to be addressed going forward. Some of the key differences are the inclusion of real-time drawing in the environment, the choice to have the customer present or available, and the use of breakout areas. The key similarities are the use of one engineer to fulfill only one domain specific role, the use of group displays, and leadership of a systems engineer, or at least someone in that role.

How these various points are integrated into a multidisciplinary concurrent engineering environment will depend on the needs and the requirements, which will be determined based on the design application. The next chapter will investigate the needs of target industries based on what has not yet been addressed by the 14 concurrent engineering environments that were surveyed.

The combined summary of the specific hardware, software, and peopleware decisions that have been made at each environment are shown in Table 15.

Table 15: Summary of Hardware, Software, and Peopleware Decisions by Environment

	PDC	ASDL	CDC	SRDC	CDF	ICDF	SSAL	IMDC	Total	Percentage
Hardware										
Individual Engineering Support Systems										
External Mobile	■	■							2	25%
Mobile Preconfigured				■					1	13%
Permanent Desktop	■	■	■	■	■	■	■	■	8	100%
Platform and Server Support										
Information Server	■	■	■	■	■		■		6	75%
Analysis/ Modeling Server		■			■		■		3	38%
Gateway Server		■			■	■	■	■	5	63%
Visualization Hardware										
Interactive Displays	■	■	■		■			■	5	63%
Group Displays	■	■	■	■	■	■	■	■	8	100%
Communication Hardware										
Video Systems	■	■			■				3	38%
Audio Systems	■	■			■			■	4	50%
Domain Specific Hardware										
Experimentation		■		■					2	25%
Rapid Prototyping					■				1	13%
Software										
Collaboration										
Commercial Off the Shelf	■	■	■	■	■	■	■		7	88%
Modified Commercial Off the Shelf								■	1	13%
Custom									0	0%
Analysis										
Commercial Off the Shelf		■	■	■	■	■	■	■	7	88%
Modified Commercial Off the Shelf									0	0%

	PDC	ASDL	CDC	SRDC	CDF	ICDF	SSAL	IMDC	Total	Percentage
Custom	■								1	13%
Visualization										
Commercial Off the Shelf	■	■	■	■	■	■	■	■	8	100%
Modified Commercial Off the Shelf									0	0%
Custom									0	0%
Integration										
Commercial Off the Shelf	■	■		■	■		■	■	6	75%
Modified Commercial Off the Shelf									0	0%
Custom			■			■			2	25%
Modeling										
Commercial Off the Shelf		■			■				2	25%
Modified Commercial Off the Shelf				■				■	2	25%
Custom	■		■			■	■		4	50%
Peopleware										
Definition of Roles										
Recorder		■			■				2	25%
Domain Specialists	■	■	■	■	■	■	■	■	8	100%
System Engineers	■	■	■	■	■	■	■	■	8	100%
Project Owner	■	■			■	■			4	50%
Definition of Process										
Flexible Process		■	■	■	■		■		5	63%
No Defined Process									0	0%
Defined Process	■	■				■		■	4	50%
Team Formation Strategy										
Temporary Teams		■	■	■					3	38%
Standing Teams	■				■	■	■	■	5	63%
Consultative Teams	■	■	■		■				4	50%
Internal Teams	■	■	■	■	■	■	■	■	8	100%
Team Size	■	■	■	■	■	■	■	■	8	100%
Conflict Resolution Strategy										
No Defined Strategy	■	■	■	■	■	■	■	■	8	100%
Defined Strategy									0	0%
Degree of Concurrency	■									

	PDC	ASDL	CDC	SRDC	CDF	ICDF	SSAL	IMDC	Total	Percentage
Allow for Remote Participants	■	■	■	■	■		■		6	75%
Completely Concurrent	■		■		■	■		■	5	63%

CHAPTER SIX:

ADDITIONAL NEEDS OF CONCURRENT ENGINEERING ENVIRONMENTS

When the PDC and CDC were established they were considered paradigm shifts in the aerospace industry. Now, companies are in the aerospace industry are not competitive unless they are using a concurrent engineering environment [37]. All of the centers surveyed were developed for on particular industry or type of mission, no attempt has been made to develop a multi industry, multi mission concurrent engineering environment. It is anticipated that a model of multi domain specific subsystems will be required in most large scale designs. Key differences and additional requirements call for alternations to the environments surveyed in the previous chapter. In order to allow that this concurrent engineering environment can serve multiple industries the general design considerations for the aerospace, defense, and automotive industry will be examined.

Concurrent Engineering Design Needs of Aircraft Industry

The needs of aerospace in concurrent design have been well documented considering this industry is the only one served by concurrent engineering environments. However, the focus of the concurrent environments surveyed is space flight or satellite design. Design of earth borne aircraft will require a separate set of hardware, software, and peopleware configurations then have been discussed in the surveys above.

Although the modifications to accommodate aircraft into the existing spacecraft focused concurrent engineering environments are not needed, changes to the designs will occur. The missions of inter atmosphere aircraft is less specified and narrowly scoped than that of space flight capable crafts in that the specific objectives could change throughout the life of the design article while a satellite rarely changes function after launch. The environments that aircraft will operate in may again vary over its life compared to the environmental conditions a spacecraft will see.

Concurrent Engineering Design Needs of Defense Industry

The defense industry frequently designs large scale platforms with multiple systems integrated. The missions are specific at the outset but the designs require flexibility as defense needs change over the commonly 30 year life of the design articles. Based on my experience in the defense industry, the key differences from the aerospace industry are the requirements for protection of defense secrets and the number of stakeholders required to agree to separate aspects of the design.

Security Requirements

Security comes in two forms, classified and restricted unclassified. Restricted unclassified can include provisions such as No Foreign Participation, NOFORN and For Official Use Only, FOUO which limit the domain specific experts that can participate in a design session. Classified restrictions can include Confidential, Secret, and Top Secret with additional requirements if the design is on Sensitive Compartmented Information (SCI) or Special Access Programs (SAP). Obtaining a security clearance can take anywhere from 6 months to 18 months depending on the amount of background checking required. If a particular domain expert is required, this could delay design sessions or require the identification of an already cleared domain expert.

Both types of security forms, Classified and Restricted Unclassified, complicate other aspects of the design other than personnel. Document handling and even the facility will have specific lockdown requirements such as special locks, facility construction, and safeguarding. Features such as a permanent ceiling as opposed to a standard drop ceiling may be required and difficult to modify in an existing concurrent engineering environment. A connection to a secure network will be required to host secure phone calls and data transmissions outside of the facility to customers and stakeholders who are not present. Significant additional hardware and facilities costs can be added to the establishment of a concurrent engineering environment capable of handling government classified and restricted design information [65].

Number of Customers and Stakeholders

In government design, there are numerous customers and stakeholders that need to agree with and approve design features. Each subsystem such as power plant, weapons, structures, and propulsion have both a design authority and a warrant holder. For a moderately straight forward design 15 subsystems might be present for a total of 30 stakeholders not including the systems level warrant holder and the program office owners for a total of 33-35 stakeholders for a systems level design. The capability to communicate with the stakeholders is vital and will be required in a center performing concurrent engineering on government designs.

Concurrent Engineering Design Needs of Automotive Industry

The design of automobiles has become increasingly more complex. Systems have grown to include integrated computers, complex electronics, and hybrid propulsion technologies. The need to push the technological envelope has automakers in the US chasing the success enjoyed by Japanese automakers with concurrent engineering. The US industry has not been able to evolve their processes to the point required to support concurrent engineering that includes suppliers in the design [66]. The issues surrounding incorporation of suppliers into the current engineering process include protection of Intellectual Property (IP) and integration of outside customized tools resulting from the integration of multiple suppliers in the design process.

Integration of Custom Tools

The automotive industry has evolved to a tiered supplier system where the second tier of manufactures often designs and builds the components concurrently with the automobile manufacturer [66]. As a result the automobile manufacturer can remain lean and rely on the design experts at the second tier level. These designers commonly have custom design tools for their domain specific design that would need to be integrated into the concurrent engineering environments system model. So far, the environments surveyed with custom tools have developed the tools themselves or at least own the information and can permanently integrate them into the environment. A multi-industry would have the issue of not owning the custom tools and needing to integrate several custom tools into a design session that may all change by the next design session.

Intellectual Property Protection

A trust relationship must be built between the concurrent engineering environment operators and the domain expert that the information given to them from a domain expert will not be given to a competitor that could potentially offer the solution at a lower cost; that would undermine the openness in design required in a concurrent engineering environment design session. So, along with the issue of integrating customized tools from second tier suppliers comes the issue of protecting the IP and trade secrets that sets one company apart from another as domain experts. The integration of tools onto a server and the introduction of design information into a session must be done in such a way that this information is protected. Kliner asserts that there is a need for Intellectual Property Protection (IPP) when sharing engineering data between development partners [67]. Kliner also mentions that tools exist to protect IP but have so far not been included in industry or in any of the concurrent engineering environments surveyed [67]. This is a gap that needs further investigation.

Conclusions

In moving the application of concurrent engineering environments from solely aerospace to multiple industries, additional concerns need to be addressed on top of the best practices currently in use at existing environments. By combining the information surveyed with prescribed solutions for the aforementioned specific issues a concurrent engineering environment can be established to support multiple industries. A notional facility will be proposed in the following chapter based on best practices and literary research.

CHAPTER SEVEN:
RECOMMENDATIONS AND FUTURE WORK

All of the Concurrent engineering environments surveyed have noted general success after implementation; however, they all have been focused on Aerospace, specifically spacecraft or satellite design. I propose that the benefits of time and cost savings referenced in Figure 2 can be leveraged into other industries through the development of a multidisciplinary, multi-industry concurrent engineering environment.

Comparison

Table 16 compares the concurrent engineering environments surveyed in each the hardware, software, and peopleware configuration categories.

Table 16: Comparison of Concurrent Engineering Environments Surveyed

Category	Total	Percentage
Hardware		
Individual Engineering Support		
External Mobile	2	25%
Mobile Preconfigured	1	13%
Permanent Desktop	8	100%
Platform and Server Support		
Information Server	6	75%
Analysis/ Modeling Server	3	38%
Gateway Server	5	63%
Visualization Hardware		
Interactive Displays	5	63%
Group Displays	8	100%
Communication Hardware		
Video Systems	3	38%
Audio Systems	4	50%
Domain Specific Hardware		
Experimentation	2	25%

Rapid Prototyping	1	13%
Software		
Collaboration		
Commercial Off the Shelf	7	88%
Modified Commercial Off the Shelf	1	13%
Custom	0	0%
Analysis		
Commercial Off the Shelf	7	88%
Modified Commercial Off the Shelf	0	0%
Custom	1	13%
Visualization		
Commercial Off the Shelf	8	100%
Modified Commercial Off the Shelf	0	0%
Custom	0	0%
Integration		
Commercial Off the Shelf	6	75%
Modified Commercial Off the Shelf	0	0%
Custom	2	25%
Modeling		
Commercial Off the Shelf	2	25%
Modified Commercial Off the Shelf	2	25%
Custom	4	50%
Peopleware		
Definition of Roles		
Recorder	2	25%
Domain Specialists	8	100%
System Engineers	8	100%
Project Owner	4	50%
Definition of Process		
Flexible Process	5	63%
No Defined Process	0	0%
Defined Process	4	50%
Team Formation Strategy		
Temporary Teams	3	38%
Standing Teams	5	63%
Consultative Teams	4	50%
Internal Teams	8	100%
Team Size	8	100%
Conflict Resolution Strategy		
No Defined Strategy	8	100%

Defined Strategy	0	0%
Degree of Concurrency		
Allow for Remote Participants	6	75%
Completely Concurrent	5	63%

This comparison of existing environment configurations, representing successful implementation of software, hardware, and peopleware, as well as the additional needs for a multi-industry/ multi-domain environment was considered when developing the recommended configuration.

Proposed Environment

The environment described below is a combination of best practices of the current environments and the accommodations required to fulfill the needs of the aircraft, automotive, and government industries. The environment will need to be flexible in its ability to reconfigure to changing needs. First, the variations from best practices will be discussed followed by the design of the environment, and future work.

Intellectual Property Protection

IP will need to be protected in order to assure the domain experts in the field that their information will not be divulged to competitors or customers that may misuse their custom tools and methodologies. The first accommodation that can be made for IP is the ability to accommodate Laptops in a kiosk setup so that IP can remain on the user's computer, allowing them to protect their information. A similar setup is used in the Space System Rapid Design Center at Ball Aerospace and Technologies Corporation [8].

The second modification that should be made is closed and separate breakout rooms should be available to have direct discussions with the customer or between domain experts from the same company regarding the inter-workings of their custom tools if required. Breakout rooms are used at other environments but most are open with glass or hear-through walls that will not support a private conversation [7,24].

The final way to ensure IP is protected is to establish the concurrent engineering environment at a company who can remain an honest broker, has no desire or reason to want to steal or give away IP. This honest broker setup is similar to the approach to conducting research projects at SCRA. There they outsource all of the work to domain experts while retaining oversight and the duties of integration of the experts. They also retain no IP and ensure that it is protected through the research process.

Support for Classified Projects

In order to accommodate classified projects one must look to the NISPOM for guidance. The NISPOM defines in great detail the requirements for obtaining personnel clearances and building a classified space. Some of the key issues are restricting access to the space, logging access events, maintaining oversight over who participates, and safeguarding classified hardware and documents when not in use [65].

The issues associated with logging persons whom entered the room, accessed classified hardware, and generated classified data can be accomplished in many ways. Personal Identification Numbers can be given to the cleared individuals to allow them access to the room and to the hardware. Biometric tools could also be used to identify and log individual access [65].

Safeguarding the data, documents, and hardware can be accomplished with safes and secure server rooms that are only accessible by employees of the Concurrent engineering environment. When not in use, classified computers can be locked up with classified documents. This is all the more reason to build the facility with kiosks and removable preconfigured laptops. This way the facility can switch from classified to unclassified by replacing the laptops and switching access from the classified servers to the unclassified servers [65].

Research Sandbox

The environment should also accommodate the ability to run mission scenarios in a classified setting to support war games for the government. One common feature used during mission planning is a sandbox, a literal box of sand or similar set of materials that can be reconfigured to match terrain and conditions during the planning process. This could also be accomplished by a multi-touch interface table in a centralized location [30]. Although some of the environments surveyed use centralized tables in their layout and 5 use interactive displays, none combine the two concepts into an interactive digital sand table concept.

Environment Layout and Features

The workstations to be included in the proposed environment should include 20 kiosk style workstations that can accommodate either one unclassified preconfigured laptop, one classified laptop, or a non standard designer supplied laptop. Of the environments surveyed, only one accommodated more than 20 workstations and most of those were left unpopulated during a design session [23]. Most of the other design environments had 15 or less workstations; I propose that more would be required for this environment because of the potential for large customer/stakeholder groups that may attend the design sessions. By using kiosks instead of preconfigured desktops, the environment will support outside experts with their tools as well as classified laptops that can be locked away when not in use as required by the NISPOM [65].

Three group displays should be used in the environment to facilitate the display of group design information, presentations, and video teleconferencing with the group. They could of course all be used for any one of those functions simultaneously but having the ability to do all three at the same time is important and common in the environments surveyed, 100% of the environments included group displays [23,62].

In order to facilitate active sketching two smart boards should be used, one located such that meeting notes and modifications can be made in a group setting and one set aside for side bar discussions not affecting the full group. I stress that they should be smart boards and not white boards so that information sketched and noted can be saved and disseminated. Since drawing is sketching and drawing has been noted as important to concurrent engineering environments, LCD sketch pads should be provided at each workstation to facilitate sketching in a manner that can be saved and disseminated easily. One additional graphic user interface is the Microsoft touch table which can be used for the creation or review of models, sketches, or mission plans (i.e. a sand table) [30].

The capability for audio and video communication is vital for this environment. Due to the large number of stakeholders/customers that could not be accommodated in the room, communication via video teleconference or web chat will be important to communicate issues and solutions with the customer groups. The ability to record the sessions would also be a convenient way to review the logic behind key decisions for which the customer may not have been present.

The last piece of hardware, which would be optional and largely depend on investment capital available at the time of construction, would be rapid prototyping hardware. This type of hardware is used at TRW's Integrated Concept Design Facility for rapidly producing scale models of potential solutions. The benefits noted at TRW certainly are compelling enough to include provisions for a rapid prototyping machine [19]. Additionally, there is a country wide shortage of facilities that can fabricate classified rapid prototypes for testing, mold development, or verification. This added capability would not only benefit the environment, it could benefit government classified research as a whole.

Significant development work is necessary in the area of customized software specifically designed for concurrent design. Software is required to pull subsystem design information from software to build the system model. The current methods of linked excel sheets have been successful at JPL, ESA, and other concurrent engineering environments; however, those centers also note that there are limitations and a more real-time, automated software solution would be more desirable [23,29]. These tools have the arduous task of integrating with existing software while remaining flexible enough to accommodate custom tools that have been developed or will be developed.

Another key development that is required is software to control the audio, video, and group display interaction. Allowing individual users to control the group displays in an orderly fashion while projecting their image and recording a session is an issue that does not have a COTS solution that could be easily applied to a concurrent engineering environment. Only 38% of the environments surveyed had both audio and visual systems however the additional requirement of large stakeholder groups will drive the need for those systems in a multi-industry environment.

No clear software has an advantage over another in the areas of visualization, statistics, analysis, FEA, documentation, or collaboration. These software solutions tend to follow user preferences at individual concurrent engineering environments. An additional benefit of allowing users to bring their own computers is that they will have access to their preferred software packages.

Peopleware decisions vary widely among the concurrent design centers with a few exceptions. Every center has at least one systems engineer present for the design sessions. Ideally, because systems engineering is based on experience, one seasoned systems engineer and one apprentice systems engineer should be present. Having two systems engineers present will allow issues to be handled by one while the other continues to facilitate the design meeting. Additionally, almost all of the environments surveyed recognized the importance of having the customer present during the sessions, either physically or via video conferencing/web-ex. Due to the large number of potential customers required for certain types of design, video conferencing and web-ex will be required to loop in the customer and stakeholders. One customer should be present based on the environments surveyed.

A minimum of two design sessions should be held. Logistically, because most of the talent will travel for these meetings, large gaps between sessions should be avoided to help avoid travel costs associated with using consultants. The other environments also suggest that the length of the sessions per day should be between 4-6 hours, that way offline work and other work can be performed each day, allowing the experts to avoid falling behind on their other duties at their home organizations [23,41].

A notional layout of the recommended concurrent engineering environment can be seen below in Figure 53. The workstation layout is in the common U shape. The room will have one secure access point and separate, private breakout areas.

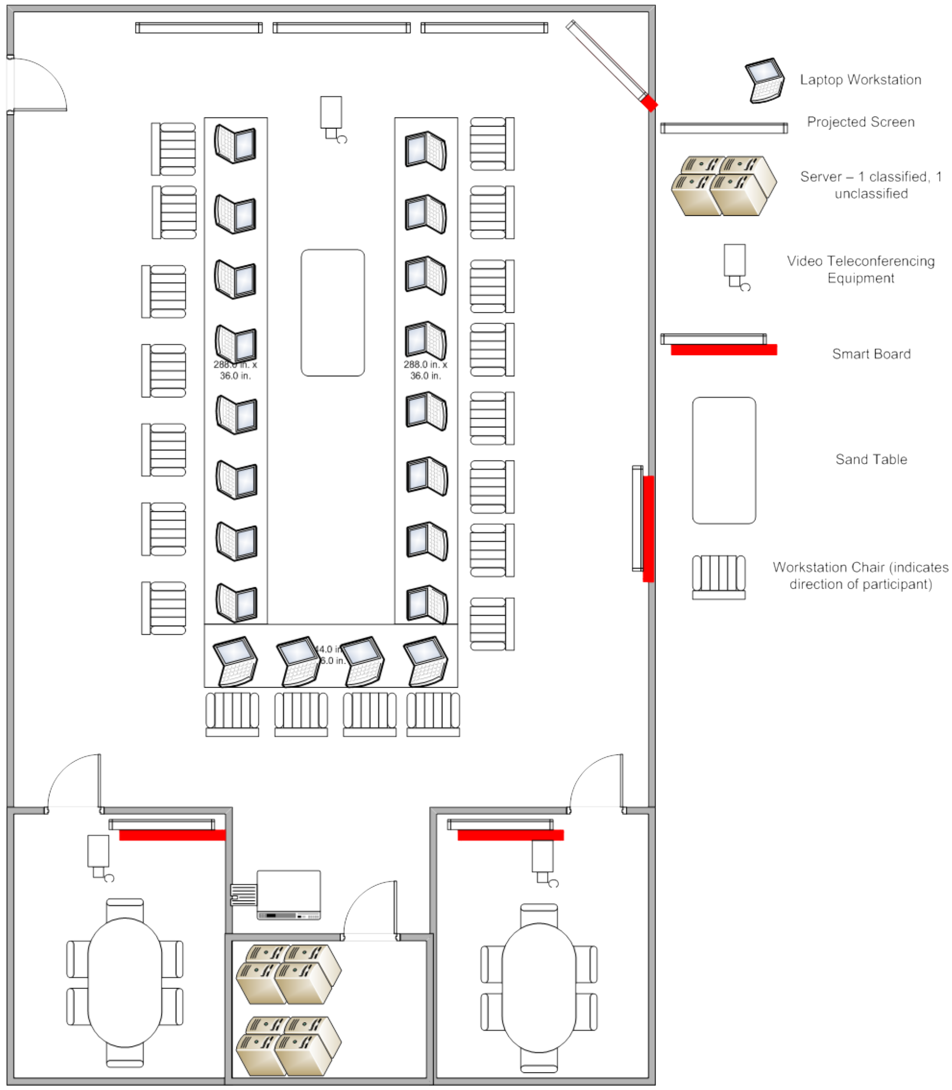

Figure 53: Notional Design of a Multidisciplinary Concurrent Engineering Environment

Summary of Features and Configuration

Table 17 is a summary of the features that are recommended for a multidisciplinary/multi-industry concurrent engineering environment. These recommendations are based on the surveys and the needs research conducted in this document. These recommendations should be considered a starting point and require field testing.

Table 17: Multi-Industry/Multidisciplinary Concurrent Engineering Environment Proposed

	Multi-Industry/Multidisciplinary concurrent engineering environment Proposed	**Comparable Surveyed Environment**
Hardware		
Workstations	20	PDC, IMDC
Monitors per Workstation	1	PDC, CDC, ASDL, SRDC, ICDF, SSAL, IMDC, SSR, SDO, LSDM
Servers	1	PDC, CDC, SRDC, CDF, ICDF, SSAL, IMDC, SSR, SDO, LSDM
projected screens	3	CDC, ASDL
Smart Boards	2	ASDL, CDF
Whiteboards	0	IMDC, PDC,
LCD Sketch Pads Interface to PC	20	ASDL
Touch Interface Table	1	New Feature
Video Teleconference in Main Room	2	PDC, ASDL, CDF, IMDC,
Video Teleconference in breakout Room	1	ASDL, CDF
Video Cameras	20	PDC, CDC, ASDL, CDF
Microphones	20	PDC, CDC, ASDL, CDF, IMDC
Domain Specific Hardware Used	Yes - If Available or Required	ASDL, CDF
Software		
System Model Generation	Custom Tools to Link Software with accommodations for non-standard custom tools	ICDF
Domain Specific Software Installed	No or limited amount	New Feature

	Multi-Industry/Multidisciplinary concurrent engineering environment Proposed	**Comparable Surveyed Environment**
Visualization	One Type of CAD program otherwise Domain Expert will Provide	IMDC
Collaboration	Microsoft Project and Web-Ex or similar; custom PDM Software for documents and data; Custom room audio/video controls	PDC, CDC, ASDL, SRDC,
Specialized	As required, Domain Expert Specified or Provided	New Feature
Modeling & Simulation	Matlab, Labview or Domain Expert provided	ICDF, SSR
Communication	MS Office Suites	PDC, CDC, SRDC, CDF, ICDF, SSAL, IMDC, SSR, SDO, LSDM
Cost	Excel or Accounting Software	PDC, CDC, ASDL, SRDC, ICDF, SSR, LSDM, DE-ICE
Peopleware		
Systems Engineers Present?	2 (at least 1)	PDC, CDC, ASDL, SRDC, CDF, ICDF, SSAL, IMDC, LSDM, DE-ICE, S^2C^2
Owners/Sponsors/Customers Present?	Yes (via webex or video teleconference if there are numerous customers) at least one present	PDC, ASDL, SRDC, CDF, ICDF, IMDC
Layout	U-Shaped	ICDF, SSAL
# of Shared Displays for Team	3	ASDL, CDF
Location of Displays	Forward	PDC, CDC, SRDC, CDF, ICDF, SDO, LSDM, DE-ICE
Who Controls Group Displays	Anyone specified by leader	ASDL, CDF, IMDC
Communication of drawings (culture)	Yes	PDC, ASDL, CDF, SDO
Data Input to System Model	Automated and Real Time	CDC, ASDL, SRDC, CDF
Video Recording Capability	Yes	ASDL, SRDC, CDF

	Multi-Industry/Multidisciplinary concurrent engineering environment Proposed	**Comparable Surveyed Environment**
Audio Recording Capability	Yes	ASDL, SRDC, CDF
Intellectual Property Handling	Yes	IMDC
# disciplines or subsystems	One expert per subsystem, as many as 20	PDC, CDC, ASDL, SRDC, CDF, ICDF, IMDC, SSR, SDO
Consultants used?	Yes	PDC, CDC, ASDL, CDF, SSAL, IMDC
Standing Design Teams?	No	CDC, ASDL, SRDC, SSAL, IMDC
Separate breakout areas?	Yes, secured	PDC, CDC, ASDL, CDF, ICDF,
Dedicated Writer	Yes	ASDL, CDF, SDO
Entire Team Required for Session	Yes	ASDL, CDF, ICDF, IMDC, SDO, DE-ICE
Industry Served	Multiple	New Concept
Type of Facility (industry, academia, government)	Industry Operated	CDC, ICDF, SSR, SDO
Minimum Sessions per Project	2	PDC,
Duration of Sessions	4-6 hours	IMDC
Duration of Design	1-2 weeks	PDC, ASDL, CDF, ICDF, SSR

In keeping with the same approach to describing the configuration, Figure 54 shows the software configuration, Figure 55 shows the hardware configuration, and Figure 56 shows the people configuration of a multi-industry/multidisciplinary concurrent engineering environment.

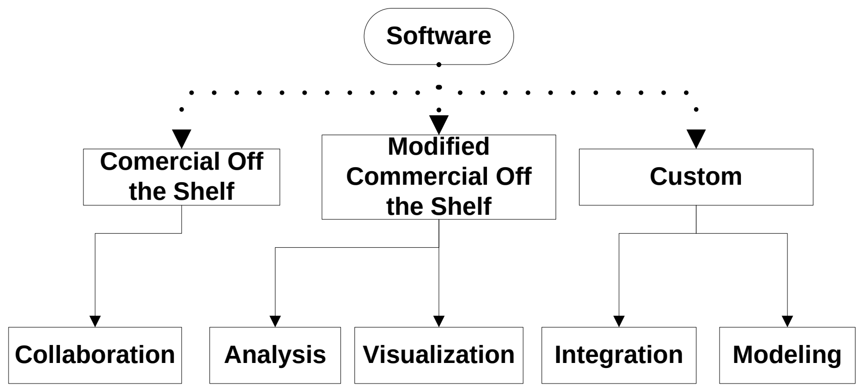

Figure 54: Multi-Industry/Multidisciplinary Concurrent Engineering Environment Software Configuration

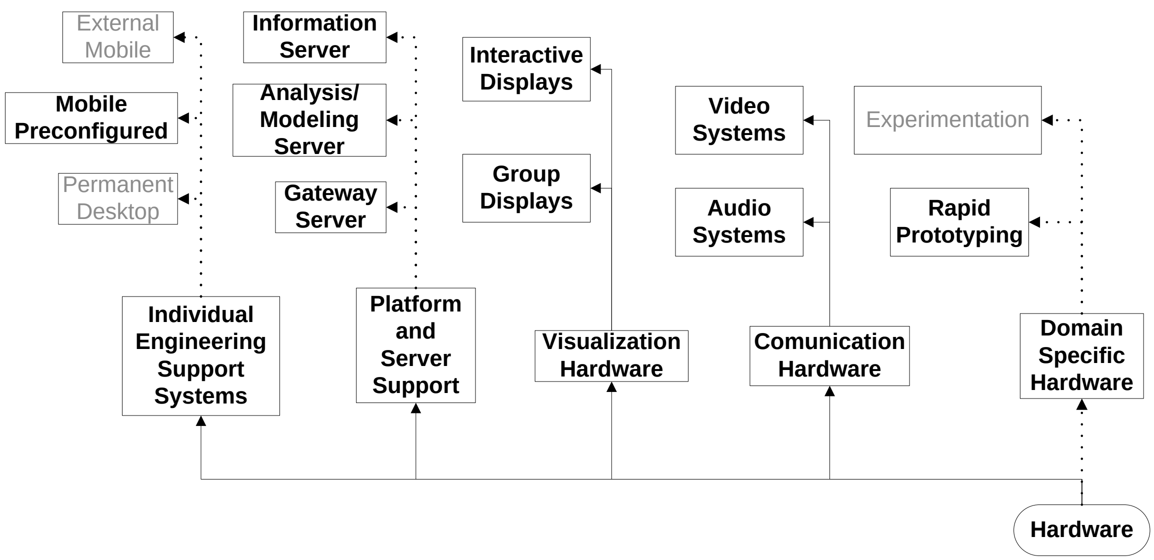

Figure 55: Multi-Industry/Multidisciplinary Concurrent Engineering Environment Hardware Configuration

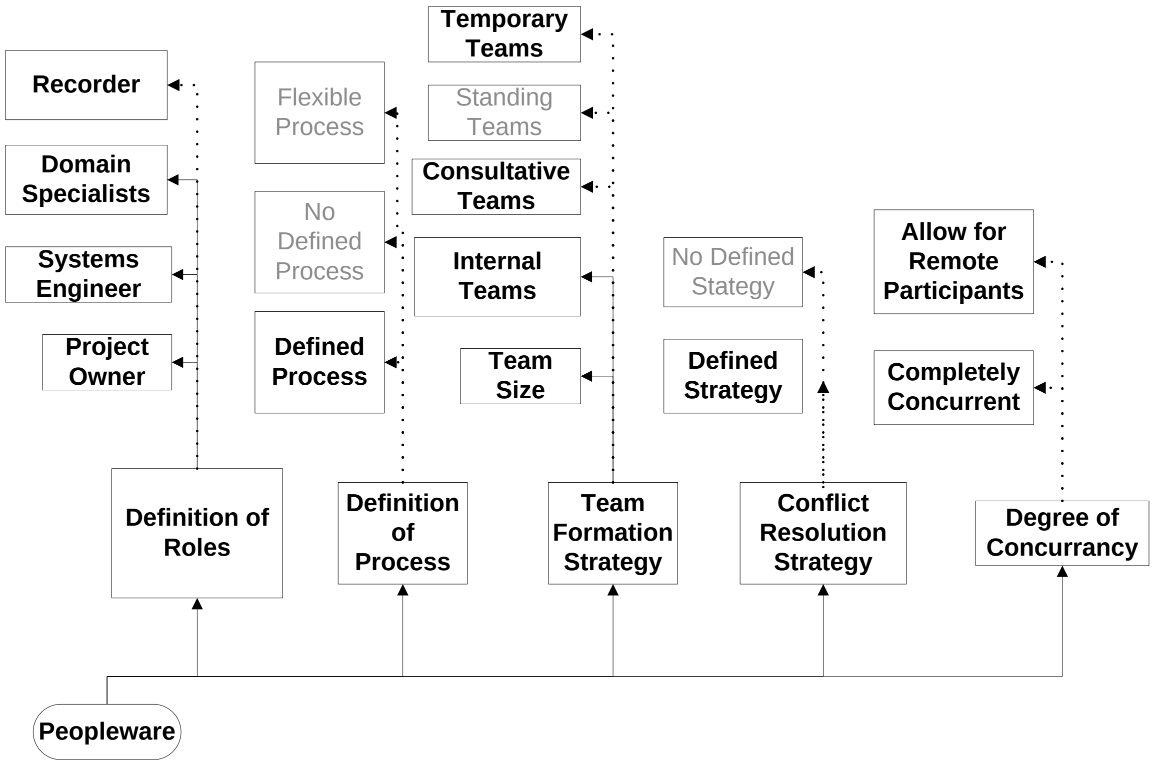

Figure 56: Multi-Industry/Multidisciplinary Concurrent Engineering Environment Peopleware Configuration

Conclusions

Concurrent engineering environments have benefited those companies in aerospace who have implemented them. These benefits are compelling enough to develop a multi-industry/multidiscipline concurrent engineering environment to serve more industries than just aerospace. Similar reductions in cost and time can be expected if the aforementioned industry specific issues can be resolved. A logical implementation site resides within SCRA and Clemson University. Further research is required and will result in a useful concurrent engineering environment for SCRA and a research test bed for Clemson University.

Future Work

Additional work is required in the area of best practices and software tool development. The literature research conducted as part of this thesis resulted in a cross section of the concurrent engineering environments that was useful in developing a concept to support multiple industries; however, additional research, including site visits to willing environments, is required. This research should concentrate on filling in the question marks left by the incomplete characterization of the environments by the available literature.

Another key development that is required is software to control the audio, video, and group display interaction. Allowing individual users to control the group displays in an orderly fashion while projecting their image and recording a session is an issue that does not have a COTS solution that could be easily applied to a concurrent engineering environment.

Significant development work is necessary in the area of customized software specifically designed for concurrent design. Software is required to pull subsystem design information from software to build the system model. The current methods of linked excel sheets have been successful at JPL, ESA, and other concurrent engineering environments; however, those centers also note that there are limitations and a more real-time, automated software solution would be more desirable [23,29]. These tools have the arduous task of integrating with existing software while remaining flexible enough to accommodate custom tools that have been developed or will be developed.

If these hurdles can be crossed it will be possible to improve the already beneficial concurrent engineering environments. These improvements will also allow the concept to jump from solely aerospace applications to multiple industries.

An Implementation Plan

Funding will be sought from internal research funding at SCRA as well as external federal funding from large weapon system program offices within the Navy and Army. A particular new Navy platform will be beginning its conceptualization within the next two – three years representing an ideal opportunity for its program office to utilize this technology and benefit from the cost and time savings that could result.

APPENDICES

Appendix A: Product Design Center (PDC) at Jet Propulsion Laboratories

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Product Design Center (PDC) at Jet Propulsion Laboratories
References	[9,5,25,41]
Hardware	
Workstations	20
Monitors per Workstation	1
Servers	1
projected screens	2
Smart Boards	1
Whiteboards	?
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	Yes
Video Teleconference in breakout Room	No
Video Cameras	Yes
Microphones	Yes
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	Pro-E
Collaboration	MS Project
Specialized	Optical Analysis (LightTools, ZeMax, Trace Pro); Thermal Design (Sinda, Tranlysis); Radiometry (Custom Spread Sheets)
Modeling & Simulation	Nastran
Communication	MS Office
Cost	Custom Spreadsheets
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	Yes
Layout	Board Room

	Product Design Center (PDC) at Jet Propulsion Laboratories
# of Shared Displays for Team	2
Location of Displays	Forward
Who Controls Group Displays	Team Leader
Communication of drawings (culture)	Yes, via Smart Boards
Data Input to System Model	Automated/Manual
Video Recording Capability	No
Audio Recording Capability	No
Intellectual Property Handling	Implied No
# disciplines or subsystems	10
Consultants used?	Yes
Standing Design Teams?	Yes
Separate breakout areas?	1
Dedicated Writer	No
Entire Team Required for Session	Yes
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Government
Minimum Sessions per Project	2
Duration of Sessions	3 hours
Duration of Design	1-2 weeks

Appendix B:The Concept Design Center (CDC) at the Aerospace Corporation

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	The Concept Design Center (CDC) at the Aerospace Corporation
References	[57,24,34,7]
Hardware	
Workstations	13
Monitors per Workstation	1
Servers	1
projected screens	3
Smart Boards	0
Whiteboards	?
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	No
Video Teleconference in breakout Room	No
Video Cameras	No
Microphones	No
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	SolidWorks
Collaboration	MS Project
Specialized	Orbital Analysis (PCSOAP)
Modeling & Simulation	Visual Basic
Communication	MS Office
Cost	Custom Spreadsheets
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	No
Layout	Board Room
# of Shared Displays for Team	2
Location of Displays	Forward
Who Controls Group Displays	Team Leader
Communication of drawings (culture)	Implied No

	The Concept Design Center (CDC) at the Aerospace Corporation
Data Input to System Model	Automated
Video Recording Capability	Implied No
Audio Recording Capability	Implied No
Intellectual Property Handling	Implied No
# disciplines or subsystems	5
Consultants used?	Yes
Standing Design Teams?	No
Separate breakout areas?	1
Dedicated Writer	No
Entire Team Required for Session	Yes
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Industry
Minimum Sessions per Project	None
Duration of Sessions	Not Defined
Duration of Design	3-4 weeks

Appendix C: The Aerospace Systems Design Laboratory (ASDL) at Georgia Technical Institute

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	The Aerospace Systems Design Laboratory (ASDL) at Georgia Technical Institute
References	[29,18,55,56]
Hardware	
Workstations	8
Monitors per Workstation	1
Servers	2
projected screens	8
Smart Boards	4
Whiteboards	3
LCD Sketch Pads Interface to PC	8
Touch Interface Table	0
Video Teleconference in Main Room	Yes
Video Teleconference in breakout Room	Yes
Video Cameras	Yes
Microphones	Yes
Domain Specific Hardware Used	No
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	Determined on an as needed basis
Collaboration	MS Project, Web-Ex
Specialized	Statistics (JPM and Crystal Ball); Mathematical Analysis (Matlab)
Modeling & Simulation	Model Center
Communication	MS Office
Cost	Custom Spreadsheets
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	Yes
Layout	Mission Control
# of Shared Displays for Team	8

Location of Displays	Immersive
Who Controls Group Displays	Individual
Communication of drawings (culture)	Yes, via Smart Boards and LCD Sketch Pads attached to PCs
Data Input to System Model	Automated
Video Recording Capability	Yes
Audio Recording Capability	Yes
Intellectual Property Handling	Implied No
# disciplines or subsystems	8
Consultants used?	Yes
Standing Design Teams?	No
Separate breakout areas?	1
Dedicated Writer	Yes, Dedicated Documentation Specialist
Entire Team Required for Session	Yes
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Academia
Minimum Sessions per Project	None
Duration of Sessions	Not Defined
Duration of Design	1-2 weeks

Appendix D: The Space Research and Design Center Laboratories (SRDC) at the Navy Postgraduate School

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	The Space Research and Design Center Laboratories (SRDC) at the Navy Postgraduate School
References	[58,34,24]
Hardware	
Workstations	9
Monitors per Workstation	1
Servers	1
projected screens	1
Smart Boards	0
Whiteboards	?
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	No
Video Teleconference in breakout Room	No
Video Cameras	No
Microphones	No
Domain Specific Hardware Used	Yes, mission specific test facilities are located adjacent to the center. (Orbit, Vibrations, Balance, etc.)
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	?
Collaboration	MS Project
Specialized	Orbital Analysis (Satellite Toolkit (STK)); Satellite Design (GENSAT)
Modeling & Simulation	Nastran, Ideas

Communication	MS Office
Cost	Custom Spreadsheets
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	Yes
Layout	Board Room
# of Shared Displays for Team	1
Location of Displays	Forward
Who Controls Group Displays	Team Leader
Communication of drawings (culture)	No
Data Input to System Model	Manual
Video Recording Capability	Yes
Audio Recording Capability	Yes
Intellectual Property Handling	Implied No
# disciplines or subsystems	9
Consultants used?	No
Standing Design Teams?	No
Separate breakout areas?	0
Dedicated Writer	No
Entire Team Required for Session	No - Offline work is allowed and sessions will be held without all team members
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Government/Academia
Minimum Sessions per Project	None
Duration of Sessions	Not Defined
Duration of Design	One Semester

Appendix E:Concurrent Design Facility (CDF) at European Space Agency

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Concurrent Design Facility (CDF) at European Space Agency
References	[50,59,60,6,23,19]
Hardware	
Workstations	30
Monitors per Workstation	1.5
Servers	1
projected screens	5
Smart Boards	2
Whiteboards	?
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	Yes
Video Teleconference in breakout Room	Yes
Video Cameras	Yes
Microphones	Yes
Domain Specific Hardware Used	Yes, Rapid Prototyping Machine Closely Available
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	CATIA
Collaboration	MS Project, LotusMail
Specialized	Attitude Control (Matrix X); Mission Analysis (IMAT);
Modeling & Simulation	EUROSIM
Communication	Lotus Notes, MS Office
Cost	ECOM Cost/Technical Database & Small Satellite Cost Model

	Concurrent Design Facility (CDF) at European Space Agency
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	Yes
Layout	Mission Control
# of Shared Displays for Team	3
Location of Displays	Forward
Who Controls Group Displays	Individual
Communication of drawings (culture)	Yes, via Smart Boards
Data Input to System Model	Automated
Video Recording Capability	Yes
Audio Recording Capability	Yes
Intellectual Property Handling	Implied No
# disciplines or subsystems	16
Consultants used?	Yes
Standing Design Teams?	Yes
Separate breakout areas?	1
Dedicated Writer	Yes
Entire Team Required for Session	Yes
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Government
Minimum Sessions per Project	None
Duration of Sessions	Not Defined
Duration of Design	1-2 weeks

Appendix F: Integrated Concept Design Facility (ICDF) at TRW

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Integrated Concept Design Facility (ICDF) at TRW
References	[37]
Hardware	
Workstations	15
Monitors per Workstation	1
Servers	1
projected screens	2
Smart Boards	0
Whiteboards	2
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	No
Video Teleconference in breakout Room	No
Video Cameras	No
Microphones	No
Domain Specific Hardware Used	No
Software	
System Model Generation	Custom Data Exchange Tool
Domain Specific Software Installed	Yes
Visualization	CATIA
Collaboration	None
Specialized	Component Selector Tool for "snap together" concept designs
Modeling & Simulation	Designer's Choice
Communication	MS Office
Cost	Custom Spreadsheets

	Integrated Concept Design Facility (ICDF) at TRW
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	Yes
Layout	U-Shape
# of Shared Displays for Team	2
Location of Displays	Forward
Who Controls Group Displays	Leader
Communication of drawings (culture)	No
Data Input to System Model	Manual
Video Recording Capability	No
Audio Recording Capability	No
Intellectual Property Handling	Implied No
# disciplines or subsystems	7
Consultants used?	No
Standing Design Teams?	Yes
Separate breakout areas?	2
Dedicated Writer	
Entire Team Required for Session	Yes
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Industry
Minimum Sessions per Project	None
Duration of Sessions	Not Defined
Duration of Design	1-2 weeks

Appendix G: Space Systems Analysis Laboratory (SSAL) Concurrent Engineering Facility at Utah State University

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Space Systems Analysis Laboratory (SSAL) Concurrent Engineering Facility at Utah State University
References	[26]
Hardware	
Workstations	13
Monitors per Workstation	1
Servers	1
projected screens	1
Smart Boards	0
whiteboards	1
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	No
Video Teleconference in breakout Room	N/A
Video Cameras	
Microphones	No
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	Solid Edge, IDEAS
Collaboration	None
Specialized	Flight Control (Satellite Tool Kit, Free Flyer); Thermal (Thermal Desktop, SindaFluint)
Modeling & Simulation	Matlab

	Space Systems Analysis Laboratory (SSAL) Concurrent Engineering Facility at Utah State University
Communication	MS Office
Cost	Small Satellite Cost Model
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	No
Layout	U-Shape
# of Shared Displays for Team	1
Location of Displays	Rear
Who Controls Group Displays	Leader
Communication of drawings (culture)	No
Data Input to System Model	Manual
Video Recording Capability	No
Audio Recording Capability	No
Intellectual Property Handling	No
# disciplines or subsystems	Not Specified
Consultants used?	Yes
Standing Design Teams?	No
Separate breakout areas?	0
Dedicated Writer	No
Entire Team Required for Session	No
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Academia
Minimum Sessions per Project	?
Duration of Sessions	?
Duration of Design	?

Appendix H: Space System Rapid (SSR) Design Center at Ball Aerospace

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Space System Rapid (SSR) Design Center at Ball Aerospace
References	[8]
Hardware	
Workstations	?
Monitors per Workstation	?
Servers	?
projected screens	?
Smart Boards	?
whiteboards	?
LCD Sketch Pads Interface to PC	?
Touch Interface Table	0
Video Teleconference in Main Room	?
Video Teleconference in breakout Room	?
Video Cameras	?
Microphones	?
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	AutoCAD Customized by a Visual Basic Engine
Collaboration	Internet Tools for Vendor Information; Live Link for Remote Collaboration
Specialized	MathCAD for Detailed Analytic Calculations
Modeling & Simulation	Matlab and Simulink
Communication	MS Office, NetMeeting
Cost	Excel

	Space System Rapid (SSR) Design Center at Ball Aerospace
Peopleware	
Systems Engineers Present?	?
Owners/Sponsors/Customers Present?	?
Layout	?
# of Shared Displays for Team	?
Location of Displays	?
Who Controls Group Displays	?
Communication of drawings (culture)	?
Data Input to System Model	?
Video Recording Capability	?
Audio Recording Capability	?
Intellectual Property Handling	?
# disciplines or subsystems	9
Consultants used?	?
Standing Design Teams?	?
Separate breakout areas?	?
Dedicated Writer	?
Entire Team Required for Session	No - Remote Participants are Allowed
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Industry
Minimum Sessions per Project	?
Duration of Sessions	?
Duration of Design	1-2 weeks

Appendix I: Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center
References	[51]
Hardware	
Workstations	20
Monitors per Workstation	1
Servers	1
projected screens	0
Smart Boards	0
whiteboards	0
LCD Sketch Pads Interface to PC	0
Touch Interface Table	0
Video Teleconference in Main Room	Yes
Video Teleconference in breakout Room	No
Video Cameras	No
Microphones	Yes - Only for Presenter
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	Virtual -Remote Designer's Choice; In Facility - IDEAS, Pro-E, AutoCAD
Collaboration	Remote Designer's Choice
Specialized	Flight Control (Satellite Tool Kit, SWINGBY,

	Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center
	GTDS,GMAN, MAnE, Custom Target Acquisition Tool, Freeflyer Engineer, Solar Cycle Modeling Tools, Mathlab, Mathmatica); Power(Electronic Power Spacecraft Simulation Tool, Solar Power Modeling Tools, Orbit Dynamics Energy Balance Too, Battery Sizing Tool, Voltage Trade Sheet, Radiator Degradation Tool); RF Communications (CLASS);
Modeling & Simulation	Pastran/Nastran, Online Launch Vehicle Selection Tool
Communication	MS Office, Data Exchange Platform
Cost	PRICE-H
Peopleware	
Systems Engineers Present?	1
Owners/Sponsors/Customers Present?	Yes - remotely
Layout	Virtual
# of Shared Displays for Team	N/A
Location of Displays	N/A
Who Controls Group Displays	Leader or individual via net meeting software, remotely
Communication of drawings (culture)	Implied no
Data Input to System Model	Manual
Video Recording Capability	No
Audio Recording Capability	No
Intellectual Property Handling	Yes - By virtue of the designers not leaving their home location.
# disciplines or subsystems	12

	Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center
Consultants used?	Yes - Almost Exclusively
Standing Design Teams?	No
Separate breakout areas?	0
Dedicated Writer	No
Entire Team Required for Session	Yes - Virtually
Industry Served	Aerospace
Type of Facility (industry, academia, government)	Government
Minimum Sessions per Project	0
Duration of Sessions	8 hours
Duration of Design	4 days

Appendix J: Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology
References	[25]
Hardware	MODELED AFTER PDC
Workstations	8
Monitors per Workstation	1
Servers	1
projected screens	1
Smart Boards	?
whiteboards	?
LCD Sketch Pads Interface to PC	Implied No
Touch Interface Table	0
Video Teleconference in Main Room	No
Video Teleconference in breakout Room	No
Video Cameras	No
Microphones	No
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	?
Visualization	?
Collaboration	?
Specialized	?
Modeling & Simulation	?
Communication	MS Office
Cost	Excel

	Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology
Peopleware	
Systems Engineers Present?	One Professor
Owners/Sponsors/Customers Present?	N/A
Layout	?
# of Shared Displays for Team	1
Location of Displays	Forward
Who Controls Group Displays	Leader
Communication of drawings (culture)	No
Data Input to System Model	Manual
Video Recording Capability	No
Audio Recording Capability	No
Intellectual Property Handling	No
# disciplines or subsystems	N/A
Consultants used?	No
Standing Design Teams?	Yes
Separate breakout areas?	No
Dedicated Writer	No
Entire Team Required for Session	No - Offline Participation Is Allowed
Industry Served	Education
Type of Facility (industry, academia, government)	Academia
Minimum Sessions per Project	N/A
Duration of Sessions	Class Period
Duration of Design	One Semester

Appendix K: Space System Concept Center (S^2C^2) at Technical University of Munich

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Space System Concept Center (S^2C^2) at Technical University of Munich
References	[25]
Hardware	
Workstations	10
Monitors per Workstation	?
Servers	?
projected screens	?
Smart Boards	?
whiteboards	?
LCD Sketch Pads Interface to PC	?
Touch Interface Table	0
Video Teleconference in Main Room	?
Video Teleconference in breakout Room	?
Video Cameras	?
Microphones	?
Domain Specific Hardware Used	?
Software	
System Model Generation	Data Base Tool MuSSat
Domain Specific Software Installed	Yes
Visualization	?
Collaboration	?
Specialized	MuSSat's
Modeling & Simulation	?
Communication	?
Cost	MuSSat's
Peopleware	
Systems Engineers Present?	One Professor

	Space System Concept Center (S^2C^2) at Technical University of Munich
Owners/Sponsors/Customers Present?	?
Layout	?
# of Shared Displays for Team	?
Location of Displays	?
Who Controls Group Displays	?
Communication of drawings (culture)	?
Data Input to System Model	?
Video Recording Capability	?
Audio Recording Capability	?
Intellectual Property Handling	?
# disciplines or subsystems	N/A
Consultants used?	No
Standing Design Teams?	Yes
Separate breakout areas?	No
Dedicated Writer	No
Entire Team Required for Session	No - Offline Participation Is Allowed
Industry Served	Education
Type of Facility (industry, academia, government)	Academia
Minimum Sessions per Project	N/A
Duration of Sessions	Class Period
Duration of Design	One Semester

Appendix L: Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT
References	[25]
Hardware	
Workstations	14 - Student Provide Their Own Laptop
Monitors per Workstation	0 - Laptops
Servers	1
projected screens	2
Smart Boards	?
whiteboards	?
LCD Sketch Pads Interface to PC	?
Touch Interface Table	0
Video Teleconference in Main Room	No
Video Teleconference in breakout Room	No
Video Cameras	No
Microphones	No
Domain Specific Hardware Used	No
Software	
System Model Generation	Linked Excel Sheets
Domain Specific Software Installed	Yes
Visualization	CAD Software
Collaboration	?
Specialized	Satellite Tool Kit
Modeling & Simulation	NASTRAN, CFD Software
Communication	MS Office
Cost	Excel

	Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT
Peopleware	
Systems Engineers Present?	One Professor
Owners/Sponsors/Customers Present?	N/A
Layout	?
# of Shared Displays for Team	2
Location of Displays	Forward
Who Controls Group Displays	Leader
Communication of drawings (culture)	No
Data Input to System Model	Manual
Video Recording Capability	No
Audio Recording Capability	No
Intellectual Property Handling	No
# disciplines or subsystems	N/A
Consultants used?	No
Standing Design Teams?	Yes
Separate breakout areas?	No
Dedicated Writer	No
Entire Team Required for Session	Yes
Industry Served	Education
Type of Facility (industry, academia, government)	Academia
Minimum Sessions per Project	N/A
Duration of Sessions	Class Period
Duration of Design	One Semester

Appendix M: The Center at Boeing Military Aircraft Company

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	The Center at Boeing Military Aircraft Company
References	[25]
Hardware	
Workstations	10
Monitors per Workstation	?
Servers	?
projected screens	1
Smart Boards	?
whiteboards	?
LCD Sketch Pads Interface to PC	?
Touch Interface Table	0
Video Teleconference in Main Room	?
Video Teleconference in breakout Room	?
Video Cameras	?
Microphones	?
Domain Specific Hardware Used	?
Software	
System Model Generation	?
Domain Specific Software Installed	?
Visualization	?
Collaboration	?
Specialized	?
Modeling & Simulation	?
Communication	?
Cost	?
Peopleware	
Systems Engineers Present?	?
Owners/Sponsors/Customers Present?	?
Layout	Round Table

	The Center at Boeing Military Aircraft Company
# of Shared Displays for Team	?
Location of Displays	?
Who Controls Group Displays	?
Communication of drawings (culture)	?
Data Input to System Model	?
Video Recording Capability	?
Audio Recording Capability	?
Intellectual Property Handling	?
# disciplines or subsystems	?
Consultants used?	?
Standing Design Teams?	?
Separate breakout areas?	?
Dedicated Writer	?
Entire Team Required for Session	?
Industry Served	?
Type of Facility (industry, academia, government)	?
Minimum Sessions per Project	?
Duration of Sessions	?
Duration of Design	?

Appendix N: Human Exploration and Development of Space Integrated Design Environment (HEDS-IDE) at Johnson Space Center

This appendix contains the background data for the surveyed concurrent engineering environment in table format.

	Human Exploration and Development of Space Integrated Design Environment (HEDS-IDE) at Johnson Space Center
References	[25]
Hardware	
Workstations	?
Monitors per Workstation	?
Servers	?
projected screens	?
Smart Boards	?
whiteboards	?
LCD Sketch Pads Interface to PC	?
Touch Interface Table	0
Video Teleconference in Main Room	?
Video Teleconference in breakout Room	?
Video Cameras	?
Microphones	?
Domain Specific Hardware Used	?
Software	
System Model Generation	?
Domain Specific Software Installed	?
Visualization	?
Collaboration	?
Specialized	?
Modeling & Simulation	?
Communication	?

Cost	?
Peopleware	
Systems Engineers Present?	?
Owners/Sponsors/Customers Present?	?
Layout	?
# of Shared Displays for Team	?
Location of Displays	?
Who Controls Group Displays	?
Communication of drawings (culture)	?
Data Input to System Model	?
Video Recording Capability	?
Audio Recording Capability	?
Intellectual Property Handling	?
# disciplines or subsystems	?
Consultants used?	?
Standing Design Teams?	?
Separate breakout areas?	?
Dedicated Writer	?
Entire Team Required for Session	?
Industry Served	?
Type of Facility (industry, academia, government)	?
Minimum Sessions per Project	?
Duration of Sessions	?
Duration of Design	?

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