REVIEW OF COLLABORATIVE ENGINEERING ENVIRONMENTS: SOFTWARE, HARDWARE, PEOPLEWARE

Jonathan Osborn, Joshua D. Summers, and Gregory M. Mocko
Clemson University

ABSTRACT
This paper compares collaborative engineering environments that are reported in the literature with respect to three specific aspects: software, hardware, and peopleware configurations. A taxonomy is developed to fully describe each of the different environments. It is shown that no environment incorporates all different aspects. Using this taxonomy, an intersecting set of features from these environments may be used to develop future environments for customized purposes.

Keywords: concurrent engineering, collaborative design, design environments

DEFINITION OF CONCURRENT DESIGN ENVIRONMENTS

This paper compares different concurrent engineering environments to extract best practices to systematically define new environments for different purposes and objectives. A Concurrent Engineering Environment (CEE) is a system and workspace that includes hardware, software, and peopleware systems that is used in facilitating design collaboration and concurrent engineering. More specifically, a CEE is defined as any environment, from physical [1] to virtual [2], designed to facilitate concurrent engineering with multiple domain experts real time. The Jet Propulsion Laboratory have been using CEEs for several years [3], realizing significant benefits in terms of reduced cost and time for increased missions (Figure 2).

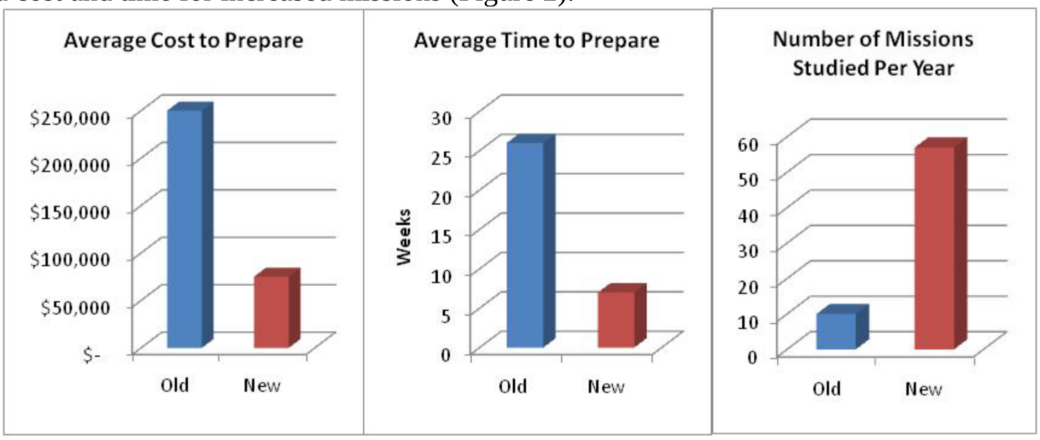

Figure 2: Concurrent Engineering Environments Benefits [3]

Concurrent engineering environments, also known as Concurrent Design Environments, Concurrent Design Centers, Design Studios, Collaborative Design Environments, can be used purposes such as proposal development, 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 [3]. As design is an iterative process [4], these activities may reoccur throughout the development project [5]. 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.

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 [6]. A basic taxonomy of concurrent engineering design software is developed to use for comparing the different CEEs. A visual representation of the software classification scheme is shown in Figure 4. 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.

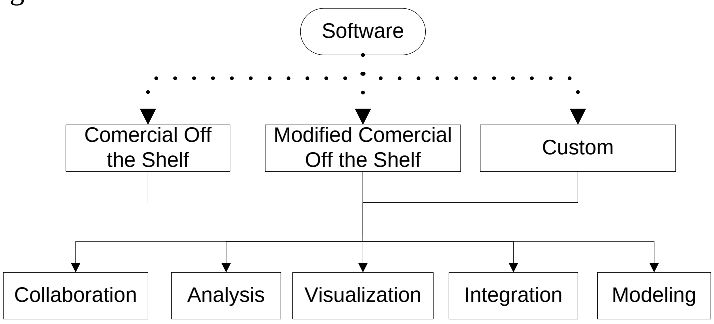

Figure 4: Software Decision Tree

The different types of software include: collaboration (such as internet vendor databases [2] or remote meetings of distributed personnel [7]), analysis (mathematical compilation tools such as or Simulink[1], finite element analysis tools such as NASTRAN[2], or statistics packages such as Crystal Ball[3]), visualization (such as CATIA[4]), integration (such as PDXpert[5]), and modeling (such as MS Excel spreadsheets to integrate the subsystem designs into a system model [8,9] or the Small Satellite Tool Kit [10]). Different combinations of software are found in each CEE.

In addition to the purpose of software, the level of software customization is also included in the taxonomy. Organizations may or may not customize software tools for their specific use. One reason to modify COTS software is to make use of opportunities for custom automation. The three levels of software customization: COTS or no customization, Modified COTS, and Custom Built Tools [11,6].

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.

Hardware for the individual engineer may include permanent desktop systems, mobile preconfigured systems within the CEE, and support for external mobile systems. A limitation of the permanent desktop system and the mobile preconfigured systems is that any additional non-standard required tools would need to be added prior to a session, requiring additional setup considerations [8,12,13]. Allowing the individual users to bring their own laptop systems with interfaces the user is most familiar is convenient but requires additional effort to accommodate the range of settings [8,14].

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[1] www.mathworks.com/products/simulink
[2] www.mscsoftware.com
[3] www.oracle.com/crystalball/index.html
[4] www.3ds.com/products/catia/welcome/
[5] www.buyplm.com

Different dedicated servers that are found within CEE's include information, analysis, and modeling servers. 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 [9]. Visualization hardware is divided into group displays and interactive displays. Group displays are meant to pull the users into the information graphically and are important tools for coordination in a concurrent engineering environment [15]. Both audio and video communication systems for communication both internal and external to the environment. 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 group [10]. A microphone system, either for the presenter or one for each participant can be used to facilitate verbal communication. 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 [16]. Finally, the domain specific hardware that is found on-site at the CEE may include prototyping [10] and experimental capabilities [16].

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.

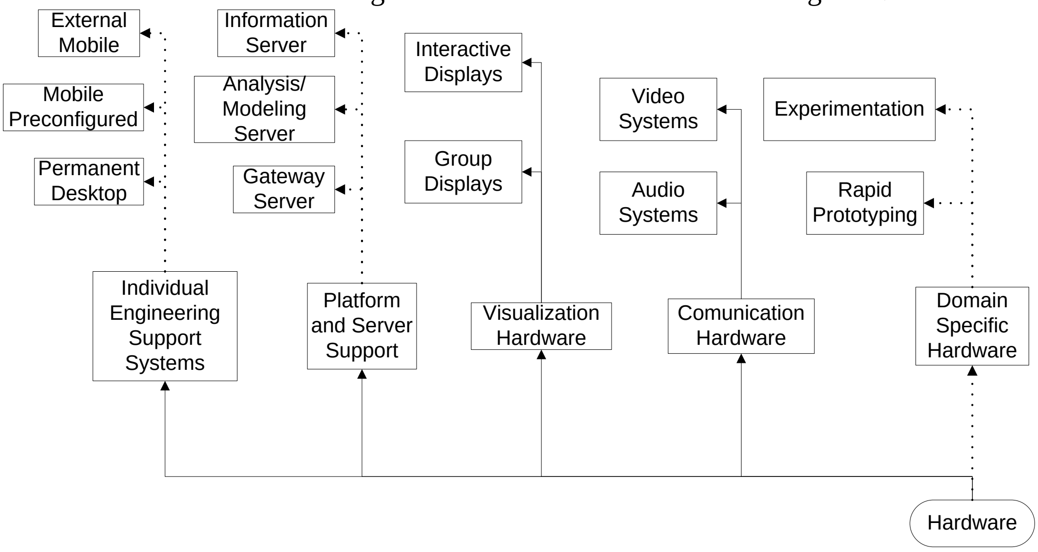

Figure 6: Hardware Decision Tree

Concurrent Engineering Peopleware

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 [17]. Austin, *et. al.* confirmed that team introductions, pooling of knowledge, and team maintenance accounts for 10-20% of design time [18]. 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.

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 [19]. A multi-disciplinary team will encounter communication and organizational challenges which must be dealt with before, during, and even after the design [17]. The roles defined by most of the centers are project owners (customers, project managers, and stakeholders) [20,10,21], system engineers, various domain specialists [12,22], and recorders [23].

Design can be a procedure driven activity of formulating a plan for the fulfillment of human need through a series of steps including problem definition, conceptualization, embodiment, and detailing [24,25,4,26]. 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. The time duration for the sessions may be 3-4 hours [27] or multi-day sessions [28]. Productivity also varies depending on the level of structure of the process with researchers suggesting that more structure tended to improve the quality of the results for novices without affecting the results for experts [29] [30].

When forming a concurrent engineering team there are a few considerations. The first would be the team size [32,33,34], ranging from eight to thirty by current industry standards; where the domain experts are pooled from, internal to the company or consultants [36]; and whether the team should become a standing team or should temporary teams be formed for each design [37].

Finally, the conflict resolution strategies employed in the CEE and the degree of concurrency of the CEE are distinguishing characteristics.

Although engineering design is meant as a technical activity, it truly functions as a social activity [17]. 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.

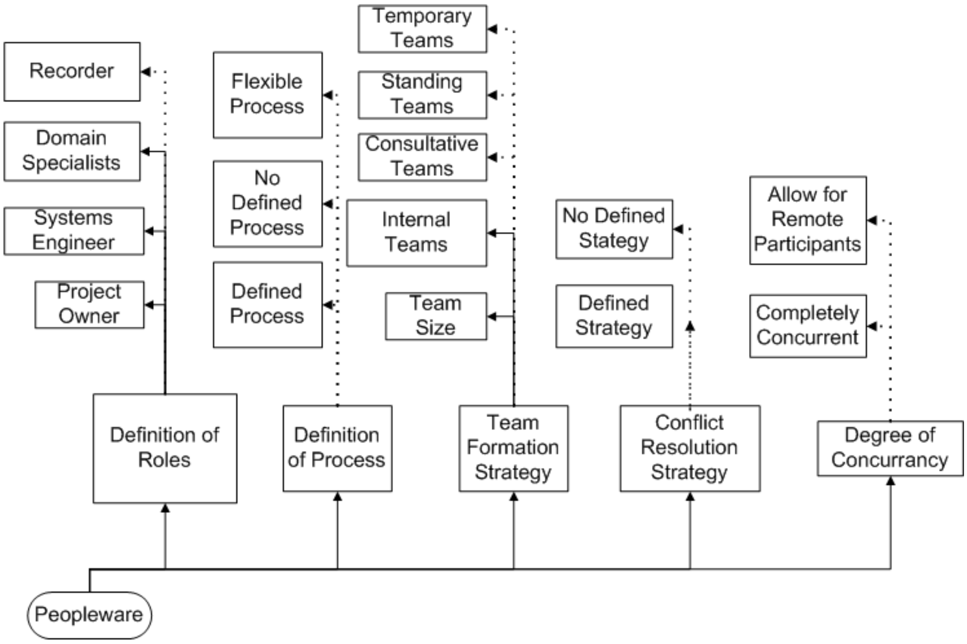

Figure 7: Peopleware Decision Tree

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:

1. Product Design Center (PDC) at Jet Propulsion Laboratories [3,1,21,27]
2. The Aerospace Systems Design Laboratory (ASDL) at Georgia Technical Institute [16,9,41,42]
3. The Concept Design Center (CDC) at the Aerospace Corporation [20,13,8,43]
4. The Space Research and Design Center Laboratories (SRDC) at the Navy Postgraduate School [44,13,20]
5. Concurrent Design Facility (CDF) at European Space Agency [10,12,36,45,46,23]
6. Integrated Concept Design Facility (ICDF) at TRW [22]
7. Space Systems Analysis Laboratory (SSAL) Concurrent Engineering Facility at Utah State University [14]
8. Integrated Missions Design Center (IMDC) at NASA Goddard Space Flight Center [37]
9. Space System Rapid Design Center at Ball Aerospace and Technologies Corporation [2]
10. Satellite Design Office (SDO) at Dornier Satellitesysteme (DSS) [47]
11. Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology [21]
12. Space System Concept Center (S^2C^2) at Technical University of Munich [21]

13. Design Environment for Integrated Concurrent Engineering (DE-ICE) at MIT [21]
14. The Center at Boeing Military Aircraft Company [21]
15. Human Exploration and Development of Space Integrated Design Environment (HEDS-IDE) at Johnson Space Center [21]

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. For brevity, only the first center is discussed in detail here. A full review of the other fourteen systems is found in [43].

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 [3]. A layout of the Team-X PDC can be seen in Figure 8.

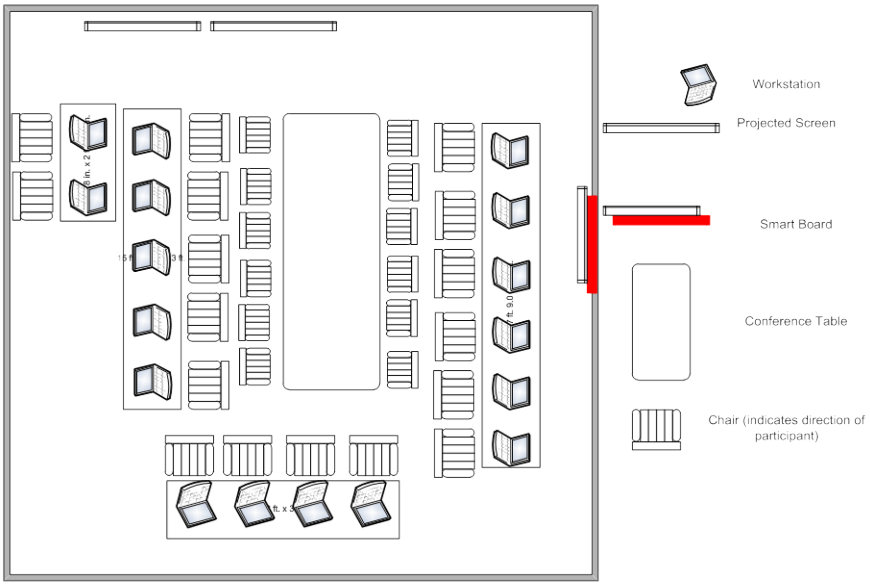

Figure 8: Team-X PDC Layout [21]

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 [1]. The PDC makes use of two types of expert teams, Team X and Team 1 [21]. 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 [1]. Team 1 was developed to perform general studies and develop proposals for JPL [21].

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 [1].

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 that the project manager controls to display any of the screens in the facility [27].

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 [27]. A visual representation of the PDC hardware layout can be seen in Figure 9.

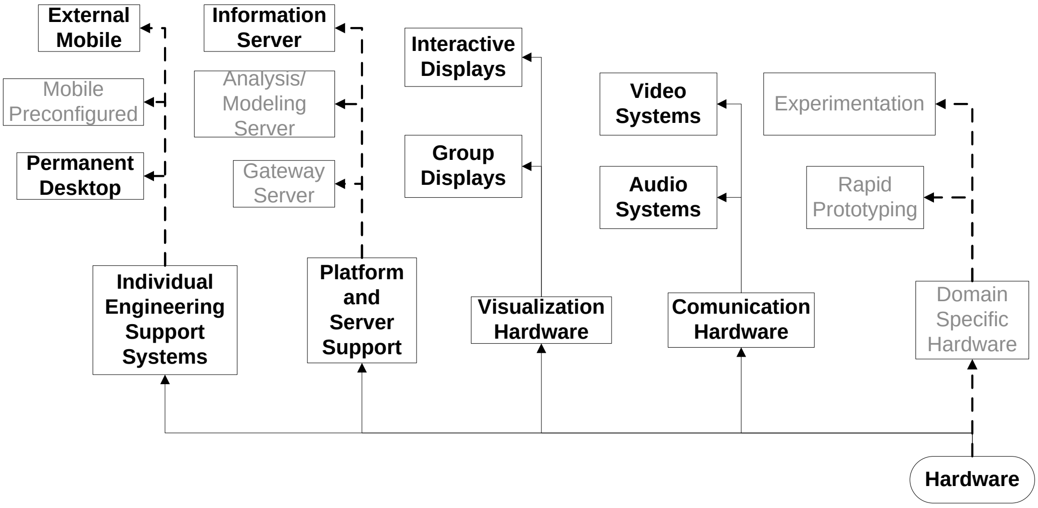

Figure 9: PDC Hardware Configuration

PDC Software

Excel based integration technologies are used to pull information from each design discipline into the systems model [21]. 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 [1]. In Figure 11 the PDC's choices in software and level of customization can be found.

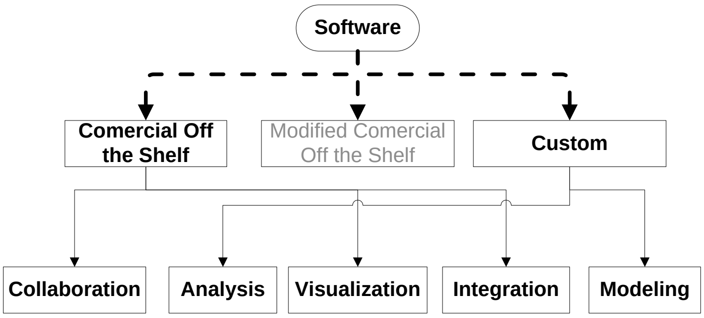

Figure 11: PDC Software Configuration

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 [3].

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 [1].

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. [1] A defined conflict resolution strategy could not be found for PDC. The peopleware configuration can be seen in Figure 13.

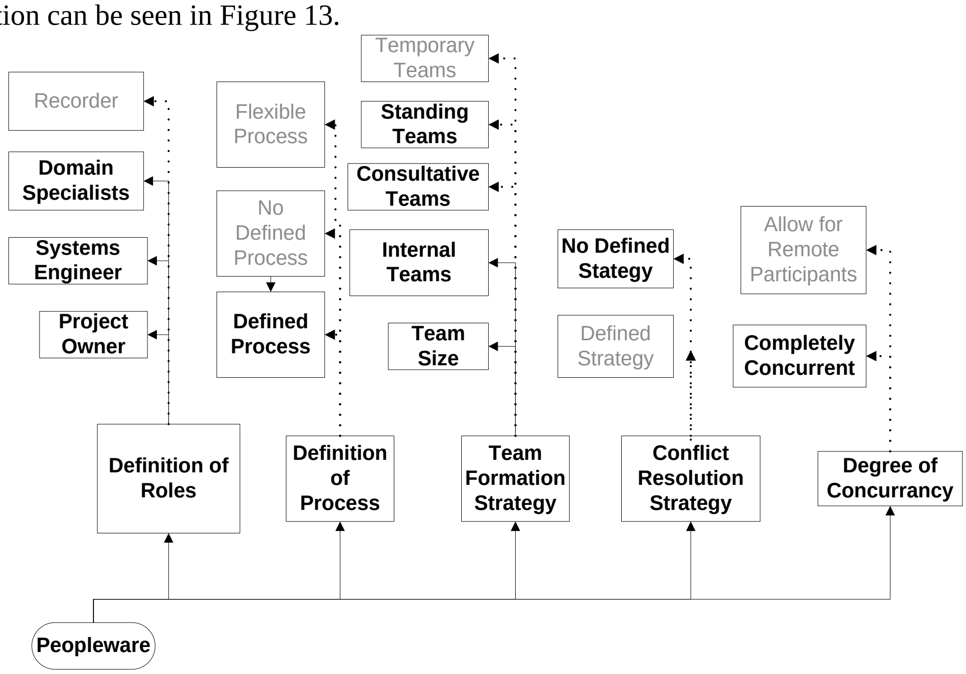

Figure 13: PDC Peopleware Configuration

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.

Table 15 provides a combined summary of the specific hardware, software, and peopleware decisions that define the reviewed environments. A few factors are common in all environments. For hardware, all systems include some permanent dedicated desktop systems and group displays for visualization. Most also include dedicated information servers, gateway servers, and some form of interactive visualization displays. With respect to software, all environments include commercial off the shelf visualization tools and most include COTS for collaboration, analysis, and visualization. Finally, for peopleware, all environments include system engineers and domain specialists formed into internal teams with defined sizes. There is no defined conflict resolution or leadership structure advocated and most provide for flexible design processes with standings teams and allow remote participants.

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. Ongoing research at CEDAR is exploring the needs of target industries based on what has not yet been addressed by the reviewed concurrent engineering requirements.

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

		PDC	ASDL	CDC	SRDC	CDF	ICDF	SSAL	IMDC	Total	%
Hardware											
Individual Engineering Support Systems	External Mobile	1	1							2	25%
	Mobile Preconfigured				1					1	13%
	Permanent Desktop	1	1	1	1	1	1	1	1	8	100%
Platform and Server Support	Information Server	1	1	1	1	1		1		6	75%
	Analysis/ Modeling Server		1			1		1		3	38%
	Gateway Server		1			1	1	1	1	5	63%
Visualization Hardware	Interactive Displays	1	1	1		1			1	5	63%
	Group Displays	1	1	1	1	1	1	1	1	8	100%
Communication Hardware	Video Systems	1	1			1				3	38%
	Audio Systems	1	1			1			1	4	50%
Domain Specific Hardware	Experimentation		1		1					2	25%
	Rapid Prototyping					1				1	13%
Software											
Collaboration	Commercial Off the Shelf	1	1	1	1	1	1	1		7	88%
	Modified Commercial Off the Shelf								1	1	13%
	Custom									0	0%
Analysis	Commercial Off the Shelf		1	1	1	1	1	1	1	7	88%
	Modified Commercial Off the Shelf									0	0%
	Custom	1								1	13%
Visualization	Commercial Off the Shelf	1	1	1	1	1	1	1	1	8	100%
	Modified Commercial Off the Shelf									0	0%
	Custom									0	0%
Integration	Commercial Off the Shelf	1	1		1	1		1	1	6	75%
	Modified Commercial Off the Shelf									0	0%
	Custom			1			1			2	25%
Modeling	Commercial Off the Shelf		1			1				2	25%
	Modified Commercial Off the Shelf				1				1	2	25%
	Custom	1		1			1	1		4	50%
Peopleware											
Definition of Roles	Recorder		1			1				2	25%
	Domain Specialists	1	1	1	1	1	1	1	1	8	100%
	System Engineers	1	1	1	1	1	1	1	1	8	100%
	Project Owner	1	1			1	1			4	50%
Definition of Process	Flexible Process		1	1	1	1		1		5	63%
	No Defined Process									0	0%
	Defined Process	1	1				1		1	4	50%
Team Formation Strategy	Temporary Teams		1	1	1					3	38%
	Standing Teams	1				1	1	1	1	5	63%
	Consultative Teams	1	1	1		1				4	50%
	Internal Teams	1	1	1	1	1	1	1	1	8	100%
	Team Size	1	1	1	1	1	1	1	1	8	100%
Conflict Resolution Strategy	No Defined Strategy	1	1	1	1	1	1	1	1	8	100%
	Defined Strategy									0	0%
Degree of Concurrency	Allow for Remote Participants	1	1	1	1	1		1		6	75%
	Completely Concurrent	1		1		1	1		1	5	63%

RECOMMENDATIONS

Concurrent engineering environments have benefited many companies and organizations in aerospace who have implemented them. These benefits are compelling enough to develop a multi-industry/multi-discipline 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. Additional issues that arise from this environment would be propriety protection of the participating organizations, strategies to handle classified materials, and the evolution of formal best practice design methods and procedures within these custom environments.

In short term, a 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.

Prior to initiating a follow-on research environment to develop further the hardware, software, and peopleware site it is recommended that site visits be conducted. This will allow the literature research in this paper to be verified and expanded upon. Further, best practices of each environment will be benchmarked. This is the next logical step towards the establishment of a test bed for further developing the required elements of a concurrent design environment.

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

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