

# Concurrent Engineering Tools: Are the Human Issues Being Ignored?

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## ABSTRACT

Concurrent Engineering (CE) tools are intended to increase the concurrency of multi-disciplinary design by integrating various enabling technologies such as computer-aided design, computer-aided manufacturing, group decision support systems, expert systems, and communication networks. If the long term viability of CE depends on effectively developing and deploying CE tools, the assumptions about how CE design tasks are most successfully performed and the roles of tools in facilitating that work should be carefully reviewed. This paper identifies the human factors assumptions made by the CE tool development community and compares them to conclusions drawn from existing literature on the role of technologies in performing technical work. This comparison suggests that the assumptions made by the CE tool development community are likely to inhibit CE tools from successfully enabling the CE process. Recommendations for remedying this state of affairs are offered in the form of restated assumptions that are consistent with documented behaviors of people using similar technologies and potential development strategies for CE tool developers.

## CONTENTS

- I Introduction
- II Research Approach
- III CE Tool Assumptions and Plausibility Assessment
  - Assumptions about Lateral Coordination
  - Assumptions of Designer's Data Needs
  - Assumptions About Human-Computer Interaction
- IV Summary and Conclusions
- References

# **Concurrent Engineering Tools: Are the Human Issues Being Ignored?**

## **I. INTRODUCTION**

Concurrent engineering (CE) is generally recognized as a practice of concurrently designing both the product and its downstream production and support processes in the early stages of design to shorten product development time, increase product and process quality, and lower the cost of production [11], [17], [59], [64], [82]. Yet according to a 1991 NSF survey [24], only 56% of U.S. manufacturing companies benchmark the product development process and few involve manufacturing formally in the concept development stage. Critical to fostering CE is the timely development and deployment of CE computer-aided design tools ("CE tools") [10], [82].

CE tools aim to increase the concurrency of design by allowing teams of designers to remotely communicate on a network and share information in a common data base [12]. CE tools include interoperable methods and tasks, an interoperable computing environment, product data management, (design) process management, and decision support capabilities [10]. A CE tool serves as an umbrella for integrating various enabling technologies such as computer-aided design (CAD), computer-aided manufacturing (CAM), computer-supported cooperative work (CSCW), distributed information systems, group decision support systems (GDSS), expert systems, multi-media and communication networks. Evidence of the perceived importance of CE tools can be found in the level of federal research funding allocated to CE tool development: \$60 million spent by ARPA (formerly DARPA) over a three year period [58].

If CE tools are necessary for the long term viability of CE, it is critical to ensure that these tools are effectively developed and deployed. Since the development of CE tools is only in its infancy, it is too early to report on success of CE deployment. However, of 20 published cases of CE

tool development reviewed, none were reported to have been successfully deployed. Disappointing results included cancellation [8], poor performance [48], limited by incomplete design process knowledge [14], [62], and working prototype but disbandment of CE tool development team [42]. Moreover, in a recent survey of the computer industry to determine which strategies accelerated product development, results indicated that the greater use of CE type tools such as CAD actually slowed the development process for some product classes (generally those with greater environmental uncertainty) [70]. Thus, it is clear that CE tool developers can benefit from guidance on the development and deployment of their tools for enhancing the CE process.

The focus of this paper is on the design of CE tools; in particular, the assumptions made by the CE tool development community about how humans successfully perform CE design tasks and the roles of tools in facilitating that work. This paper addresses the following question: Is the set of human factors assumptions made by the CE tool development community about CE tool design substantiated by experiences and literature on the role of similar technologies in performing technical work?

## **II. RESEARCH APPROACH**

The research approach consisted of two steps: 1) Content analysis of published CE tool development cases to identify assumptions of how people are expected to behave with CE technology, and 2) Comparison of those assumptions against experiences of similar technologies.

Assumptions that delimit, constrain, or influence CE tool development were identified by reviewing twenty published cases (eighteen sources) of CE tool development [8], [10], [12], [14], [15], [27], [39], [42], [45], [56], [62], [63], [66], [67], [76], [75], [79], [80]. These cases were identified through a search process using a chain sampling strategy which built upon an initial set of CE tool

cases [8], [10], [12], [15], [42], [45]. This search used industry informants and a computerized search of the concurrent engineering, product development, and computer-aided engineering literatures. The focus in the search was on identifying best practice cases in CE tool development.

The 20 cases identified during this search represent different aspects of product development activities ranging from aerospace, electronics, mechanical parts and structural design applications. CE tools are a recent development with most research and development starting after 1990. As a result, none of the tools have been completely deployed and used in industry. However, all of these cases portray their development plans and prototypical efforts as being on a successful course and thus likely, in the end, to greatly facilitate the concurrent engineering process.

Each case was reviewed to identify explicit or implied assumptions. Rather than creating a comprehensive list of design assumptions, particular attention was made to assumptions about the role of the technology in facilitating human factors of design work. This focus seemed appropriate because significant research and practical experience has concluded that successful technical implementation requires the integration of technology, organization, and people systems [19], [46], [77].

All assumptions about how people would behave with the computer tool that were explicitly stated in the publication were written down. Implicit assumptions were identified by relating an intended tool functionality (e.g., "friendly" user interface) to the implicit human factors assumption (e.g., guidelines for designing user interfaces exist). The list of phrases describing specific human factors assumptions used in each of the 20 cases were then content analyzed to find similarities. From this content analysis, the specific phrases were classified into nine generalizable assumptions. Four developers from different CE tool development projects reviewed the assumptions and confirmed that the assumptions represented those used in their own work. The nine assumptions resulting from this process are listed in Table 1 (in order of prevalence across the 20 cases), and grouped into three categories of human factors issues relevant to CE tools: lateral coordination among designers, data

needs of designers, and human-computer interaction. Table 1 also provides a brief description of how the assumption translates to decisions about the design of CE technology.

Table 1 - Summary of Assumptions

Assumption	Source	Operationalization Example
<b>Lateral Coordination</b>		
1. An integrated computing environment is sufficient for information sharing to occur.	[10], [27], [12], [63], [8], [42], [45], [15], [56], [79]	Interoperable tools and tasks enable collaboration between disciplines. [10]
2. There is a single representation of key design features that is understandable to the entire design community.	[27], [12], [63], [8], [80], [45], [15], [79]	All users simultaneously interact on a CAD data file. [15]
3. CE tools can support the interaction of multi-disciplinary teams.	[27], [12], [63], [15]	Collaboration manager establishes and terminates multiuser dialogue. [15]
4. Linking remote designers using a CE tool can substitute for their physical co-locations.	[12], [63], [15]	CE tools allow for simultaneous manipulation of shared design representations and multi-user conferencing. [15]
<b>Data Needs of Designers</b>		
5. A designer needs and wants access to all information relevant to a design.	[10], [12], [63], [39], [8], [14], [45], [15], [42]	Manufacturing process databases, design process, and cross-functional information provided to all potential users. [42]
6. Primary type of information used in design is digitally representable and context-free.	[10], [27], [12], [80], [56], [15], [62]	Information can be shared independent of the internal format via knowledge-sharing technology.
7. Design process can be codified resulting in opportunities to intelligently aid design (synthesis) activities.	[27], [12], [14], [56], [45]	Library contains sequence of design activities which specifies coordination/dependency relationships to the user. [12]
<b>Human-Computer Interaction</b>		
8. Well understood principles of enhancing human-computer interaction exists.	[8], [10], [27], [12], [14], [56], [45], [15]	An interactive environment allowing for defining specifications and constraints, selecting from design library, and modifying designs. [27]
9. Existing user interface technology is sufficient to adapt to individual differences in tool use and designer styles.	[10], [27], [8], [80], [45], [15]	CE tools accommodate different user preferences by providing varying details in the presentation of information. [15]

The next step of the research involved comparing the assumptions against experiences with similar technologies to assess their plausibility. Since CE tool development is in its infancy, a sufficient library of successful and unsuccessful cases of CE tool implementations does not yet exist from which to assess CE tool development assumptions. However, there is a wealth of knowledge gained from recent implementations of computer-based technologies that share some of the same functionalities and assumptions as CE tools, such as office automation, CAD, CSCW, and GDSS.

For each CE tool development assumption, relevant documented experiences from literatures describing the ways that people and groups interact during deployment of each of these similar technologies were reviewed. The CE tool development assumption was then compared against these documented behaviors to yield evidence for either supporting or challenging the plausibility of that assumption. Section III, which follows, describes the results of this process including the role of each assumption in achieving the intended CE tool functionality, relevant documented behaviors about how people actually interact with similar tools, and conclusions about whether the plausibility of assumptions needs to be challenged. When an assumption is challenged, the extent to which it is plausible is described. As an additional check on the outcome predicted by our plausibility assessment, shortfalls in the DARPA-funded CE tool prototype, called the Electronic Pilot Project (EPP) [45] were identified. Software deficiency was cited as the primary reason including limited tool functionality, inefficient user interfaces, lack of integration, and low reliability [48]. Most problems were human factors issues consistent with predictions of using the nine CE tool assumptions described in this paper. Finally, Section IV offers recommendations to CE tool developers for explicitly incorporating these new human factors assumptions into their technological design.

### **III. CE TOOL ASSUMPTIONS AND PLAUSIBILITY ASSESSMENT**

In this section, each of the human factors assumptions identified from the CE tool development cases are described, then assessed for their plausibility. The assumptions are grouped into three sets: communication and (lateral) coordination between disciplines, data representation for designers, and human-computer interaction of individuals.

## **A. Assumptions About Lateral Coordination**

This first set of assumptions focuses on the coordination of product development activities within an organization.

### **Assumption #1: An integrated computing environment is sufficient for information sharing to occur.**

A cornerstone of CE is information-sharing where designers freely exchange product and process information through an integrated computing environment. The assumption is that such an environment will link all project participants through an interconnected and integrated information system thereby causing a free exchange of information and coordinated design activities to occur. To the CE tool developer, an interconnected and integrated computing environment is one with interoperability between the various computers, a common storage and access mechanism, databases, and user interfaces which allows access to the design tools by all design disciplines [10]. Information sharing is thus seen to be a function primarily of technological compatibility.

The CE tool called Technique for Engineering Analysis Management (TEAM) is an illustrative example. TEAM is a prototype CE tool for satellite design which electronically couples databases and tools from the design, manufacturing, and test areas [8]. In TEAM, a knowledge base of rules was designed to take changes to one database as a trigger to initiate updates to any other linked design tool or database. The TEAM developers envisioned that a solar array designer would be notified by TEAM when test problems were encountered during solar array manufacturing and the necessary design changes could then be incorporated. The assumption among TEAM developers was that, with such interoperability provided in TEAM, design, manufacturing, and test engineers would share the information. Thus, interoperability was assumed to be a sufficient condition to enable information sharing.

### **Plausibility Assessment of Assumption #1**

Based on experiences in cooperative work and office automation technologies, the assumption that an increase in the free exchange of information will follow from the sole provision of interoperable data bases appears implausible on two accounts. The first source of questionable plausibility is that the cooperative work literature shows that creating interoperable and common databases involves more

than agreement on a set of categories (for classification) [6]; it involves sharing information structures and cognitive models of the world. For example, a manufacturing engineer's cognitive model might see manufacturing parameters as more central in ensuring successful product deployment while a design engineer might see enhanced high-risk functionalities as more central.

A second source of questionable plausibility is that information-sharing during product development involves more than exchanging engineering details of a design. Each product development activity has dialogue pertaining to the management of the design process and an interpretive context for a particular decision is exchanged as well [51]. Office automation researchers have found that such contextual dialogue includes the strategic exercise of communication through which people define, protect and pursue their interests [65].

Thus, it is unlikely that information will be exchanged freely when information sources become interconnected because individuals will continue to maintain different cognitive models for interpreting this information and different strategic interests and intents. While interoperability is an important first step, mechanisms for sharing cognitive models and finding common interests in a computer-mediated dialogue need to be developed as well.

**Assumption #2: There is a single representation of key design features that is understandable to the entire design community.**

The goal of a CE tool developer is to allow users to concurrently view design data from multiple perspectives so that multiple tasks can proceed in parallel [15]. This means that a CE tool must be developed in such a way as to allow users to interact simultaneously while operating at different levels of abstraction and with different perspectives [15], [56]. The Design Fusion project illustrates this assumption. In this project, a CE tool was built with a "database containing a single and comprehensive representation of the design and its specifications ... to support the opportunistic viewing of the design from multiple perspectives" [27, p.162]. For example, a part requiring machining could be specified so that designers, machinists, and assembly planners could develop the final specification at one time. In order to support multiple perspectives, then, CE tool developers are making the assumption that design data can be represented in such a way that the data can be interpreted accurately, differently, and usefully by all participants in the product development process.

### **Plausibility Assessment of Assumption #2**

CE tool developers draw upon the advances in CAD packages as evidence that a common representation can exist for cross-functional design activities. For example, solids modeling packages which use a geometric representation are advertised as a cross functional design tool. However, experience in CAD development also indicates that a common representation is both difficult to achieve and highly constrained. For example, the common representation typically achieved with CAD applies only to mechanical design activities or only to electrical design activities. There have been few successes at a common geometric representation that incorporates both electrical and mechanical design [55].

The difficulties in finding a common representation are understandable when considering that the representation of engineering knowledge tends to be domain-specific [40]. Some engineering domains represent their knowledge schematically, some geometrically, some mathematically, and some in computer-based languages. For example, the schematic of a circuit board for a portable tape player is the preferred representation for electronics designers but of limited use to manufacturing engineers because little manufacturing process knowledge is described. Similarly, a CE design environment also includes designers who do not use a geometric view such as those in software development, customer satisfaction, reliability, cost, and marketing. A software developer focuses on the design of data protocols and computer instructions, which are invisible to a physical object, yet have a large impact on the final product's ease of operation.

Thus, given the diversity of representations involved in the CE process and experience with CAD, the assumption that a single representation that allows for viewing a design from all perspectives is implausible. A more constrained assumption, such as achieving a common representation that ties together cognitively similar activities, such as layouts for mechanical and electrical design engineering, is more realistic.

### **Assumption #3: CE tools can support the interaction of multi-disciplinary teams.**

According to Carter & Baker [10], the primary goal of a CE tool is to increase a company's productivity by supporting the interaction of mixed-discipline teams. The hope is that "technology will bring about a revolution in team working by systematically addressing the deficiencies in the present

mode of working with CAD tools in isolation" [12, p.18]. The objective of the Collaborative Environment for Concurrent Engineering Design (CECED) project, for example, was to support "rapid interaction between team members and appropriate experts, which significantly shortens the specification and initial design phase" [15, p.48]. CE tools have also been identified as assisting team members in making design trade-off decisions amongst themselves, and even in structuring the negotiation process among team members [12]. Since there is so little discussion in any of these cases about non-technical factors facilitating teamwork, the assumption is clearly that CE tools will provide a primary, if not the, only mechanism for facilitating teamwork in the CE design process.

### **Plausibility Assessment of Assumption #3**

For CE tools to support multidisciplinary teams, the unique characteristics of team-based decision making (as opposed to individual decision making) must be incorporated into the tool's procedures, interface, and database. Factors that must be considered in facilitating effective team-based decision making in CE environments include an organizational structure and culture that focuses on project-based accomplishments versus functional responsibilities, overcoming differences in professional status among different design functions, ensuring parity in compensation between the functions, fewer organizational levels before a common report across functions is found, consensus among CE team members about project goals, team continuity, and a shared problem-solving capability [41], [69]. In addition, cross-functional team effectiveness in organizations is also impacted by the way managers decide how tasks are assigned, what tasks are overlapped, what training is done and embedded organizational culture [1], [4], [41].

In this research about CE teams, their effectiveness is found to reflect factors often unrelated to technology. While technology can make parity and status differences more painfully obvious (such as with differences in file access), even a system that is intentionally designed for equity cannot overcome differences in social and financial treatment in the workplace. Thus, we conclude that assuming CE tools can facilitate interactions of a team independent of breaking down organizational barriers and individual training considerations is probably implausible.

**Assumption #4: Linking remote designers using a CE tool can substitute for physical co-location**

CE tools are felt to provide the capability to create "virtual" tiger teams by allowing the same level of collaboration of *physically dispersed* individuals that would have been achieved through co-location [12]. This collaboration is assumed to be possible because CE tools combine the ability to simultaneously manipulate shared design representations through multi-user conferencing. The existence of both capabilities are felt by CE tool developers to provide an environment similar enough to face-to-face interaction to overcome any difficulties of distributed work [15].

**Plausibility Assessment of Assumption #4**

The jury is still out on the viability of "virtual" co-location, but the project management and computer-mediated cooperative work literatures identify many reasons that face-to-face encounters cannot be completely eliminated from a collaborative design effort. First, physical proximity has been found to be an important 'supplemental' factor for achieving cooperation because it is one of the few ways that sincerity, trust, and confidence can be built [3], [54]. Second, visible interactions have also been found to be vital to the work group collaborative process [29], [73]. The face-to-face dimension of communication is an important part of multi-person tasks since it allows for brainstorming and back-and-forth discussions[7], [50]. Finally, designers operate very much in a visual mode using hand gestures and drawings (sketches) to convey information [73].

The importance of the face-to-face dimension can be seen in a recent multi-national helicopter design project [38] using the latest in CAD/CAE technology where designers were physically co-located for several months before returning to their home countries and continuing the design effort by advanced engineering and communications technologies. Thus, given experience that virtual co-location does not replace some need for physical co-location, it is likely that CE tools cannot replace physical co-location as CE tool developers assume. In particular, those situations requiring negotiation and persuasion, such as in getting agreement on a program plan (or concept) by all key stakeholders, is facilitated by physical presence. Instead, it is likely that CE tools will only partially substitute for physical co-location in selected tasks. So guidance should be made available to designers on best practices for exchanging context-dependent information.

## **B. Assumptions of Designer's Data Needs**

The second set of assumptions narrows the focus from exchanging information within an organization to assumptions about the data needs of individual designers.

### **Assumption #5: A designer needs and wants access to all information relevant to a design.**

In the typical CE design cycle - with or without a CE tool - significant resources are consumed in acquiring and distributing information, such as locating the appropriate source for a particular type of information and retrieving the necessary data. This has led CE tool developers to focus their development effort on increasing the technological ease with which information can be stored and retrieved. In facilitating information storage and retrieval, CE tool developers have made two related assumptions. First, all CE designers want access to all data relevant to their project. Second, by making all data available to all CE participants, the designer's productivity will increase because the time-consuming steps needed to find and obtain the data will be eliminated [10]. As one exemplary case, the Intelligent Manufacturing Decision Support (IMDS) system makes all manufacturing process databases, design process, and cross-functional information accessible to all engineers in all the manufacturing departments potentially involved in a CE design effort [42]. The concept is that by making all data available, the engineers will use the data to make better manufacturing design decisions.

### **Plausibility Assessment of Assumption #5**

CE tool developers are not alone in assuming that a person wants as much information as possible. For example, Zuboff found that developers of manufacturing automation projects believed that "being exposed to data implies that a person sees, comprehends, and is appropriately responsive" to that information [84, p.297]. However, researchers in human-computer interaction have consistently found that designers do not want access to all information; rather, given the wealth of design information generated in a large project, designers have been found to want only *problem-specific* knowledge that is available within a reasonable amount of search effort making use of a small number of cognitive heuristics to determine what information is needed [35], [37]. This is because, to use all the design information, a designer would need to understand a wide range of highly technical design sub-

specialties [34]. Mere awareness of facts does not mean knowledge is understood well enough to be used [74]. The information made available to the designer creates many opportunities for product enhancement, but at a cost of an increase in knowledge, responsibilities and cognitive workload [26], [34], [43]. Processing more information than a designer is capable of, leads to missing information or encoding in a form that cannot be understood by others [61]. The best strategy for providing data to CE designers is to allow them access to only relevant (and strategically useful) information that they are capable of processing [68].

Experiences of the first author with efforts to develop an integrated satellite design-cost model found that the satellite designers rarely learn (or want to learn) the nuances of the cost processes that had been integrated into the models. In addition, cost estimators had neither the time or interest in learning about satellite design. Instead, each sub-specialty tended to rely upon the other for the acquisition, summarization, and interpretation of the data. Exchanging relevant information only when necessary is indicative of good coordination [25].

Thus, even if all information is provided in the CE tool, CE tool users would be unlikely to use it all making this assumption implausible. The abundance of data made available by a CE tool must therefore be managed so that the identification, interpretation, coordination, and integration of necessary information takes place and the capabilities of individual designers are not exceeded. Thus, rather than assume that designers want all information, an assumption that fits better with documented behavior of people interacting with technology is that designers operating in a CE environment want only information critical to their problem-solving assignment.

**Assumption #6: Primary type of information used in design is digitally representable and context-free.**

A common principle used by CE tool developers is that a CE tool should and can capture and represent all data about the product, processes, needed resources and available resources in machine form [12]. Computer-aided design and computer-aided engineering (CAD/CAE) standards that allow the interchange of information such as Standard for the Exchange of Product Data (STEP) are used to create these representations [10]. The concept is that all relevant design information can be transmitted with these data standards without loss of intent or detail [27]. For example, the objective of the Concurrent Engineering Environment (CEE) CE tool is to integrate organization-wide code

libraries and data bases capturing design intent in interactive electronic design documents [45]. Thus, the assumption is that CE design information is sufficiently context-free to be translated into a well-accepted data exchange standard.

### **Plausibility Assessment of Assumption #6**

There are barriers to utilizing digitally representable data. First, CE tool developers need to develop a system that represents multi-disciplinary information in a standardized format that can gain the CAD/CAE community's acceptance as the appropriate representation standard. It is difficult, however, to find a suitable standard within one technical discipline, such as a CAD neutral file interchange format. At least eleven standards or specifications for transferring geometric representations have been created in the past decade [23]. Part of this difficulty stems from engineering knowledge tending to contain both analytic (quantifiable) and qualitative information [20], as well as tacit knowledge not being obviously accessible to outside observers [44], [53].

A second barrier is that CE developers selectively apply design knowledge based in large part on situationally-specific constraints and opportunities. Thus, even if a single representation of the design knowledge is identified in the future, it is questionable that such information would be useful to a CE designer without descriptions of situations in which the information can be most effectively applied [74]. One product development example where situational descriptors are necessary for standardized information to be usefully applied is the limited use of standardized databases of physical attributes of factory floor layouts. Such databases typically contain equipment type, dimensions of the equipment, and building codes for locating aisle ways and utilities. However, this standardized database of physical attributes is insufficient to specify a layout since it fails to include information on the human cognitive and physical capabilities at the facility in order to assess ease of material handling and need for operator-to-operator interaction which are important for productivity and quality. For example, a U-shape layout might be appropriate for a small manufacturing cell operated by a single operator but may be too small if many assemblers are required to perform the work. A layout designer tacitly knows to consider these situational factors in layout designs and tacitly knows average sizes and capabilities and needs of the humans in the factory. While such information could be added to the standardized database, it is unlikely that any database will be sufficiently comprehensive to remove the

need for additional situationally-specific information supplied by the user.

A third barrier to utilizing digitally representable data is that designers make decisions based on implicit understanding of how design decisions relate to each other [31]. For example, a parametric sizing model of an optical telescope can resize the lenses as aperture size changes. However, at some point, the optical path becomes so compressed that the focal plane fixture no longer fits. While the telescope model can be digitally represented, models must also be constructed that describe the impact of constraints such as manufacturing limits and relationship between focal plane design and changes in aperture size. A chain-reaction of design changes must be modeled, which in turn increases the heuristic knowledge that must be represented. The present reality is that such heuristic knowledge is often not explicitly available, let alone available for sharing in an interoperable computing environment. Thus, CE tool developers need to work with designers in identifying the types of information that can be used in each generation of a CE tool.

**Assumption #7: The process of doing design work can be codified resulting in opportunities to intelligently aid design (synthesis) activities.**

To increase CE productivity, CE tool developers envision a design process in which standardized methods, procedures, sequencing, and tools are used to eliminate much of the uncertainty that currently exists in design. For example, one developer specifically states that the CE tool should "manage the flow of work and processes among mixed-discipline teams and their members ... throughout the product development cycle" [10, p.118]. The control created by a project management approach of work breakdown structures and milestones is often upheld as a model to be applied to the design process whenever possible. Embedding this project management approach in a CE tool is the obvious next logical step in controlling the design process. For example, Colton and Dascanio [14] embed a standardized project management model of the design process in their intelligent design system to "allow iterations between phases, provide continuous analysis and evaluation to aid in decision making, and provide information relative to the current state of the design" (p.13). This would mean, for example, that the CE tool would guide a structural designer through the task of considering design for manufacturability in order to complete the mechanical design cycle. The assumption is that design activities and the design process can be sufficiently structured to be captured in a computer tool and

that such a tool can aid designers in areas of the design process which may have been overlooked in the past.

### **Plausibility Assessment of Assumption #7**

Research on the engineering design process [62], implementation of CAD [51], and cognitive task analysis [57], [71] have found that it is difficult to proceduralize novel design work for either the individual designer or for a group of designers because it is difficult to formalize cognitive tasks of the design process, especially when performing creative work or incorporating new concepts. Additionally, designers often display non-normative behavior that is not modelable by mathematical and algorithmic aspects of decision tools [78]. Finally, it is typically only during detailed design when the degrees of freedom within a design have been significantly reduced that a design process (such as drafting or standards-checking) can be codified.

When groups of people are involved in the design process, their patterns of interactions make the design process even more complex, transitory, and unpredictable than when designs are created by individuals alone [60]. For example, the metrics of Design-For-Assembly (DFA) are easily codified as a design criteria. However, the process of implementing DFA in the design requires a host of human skills (akin to managerial skills) such as persuasion, cooperation, and degree of authority to make the trade-offs with competing criteria. A product that is easy to assemble with plastic snap fasteners is often difficult to repair. Deciding if ease of assembly or ease of repair is more important and then convincing all stakeholders of the trade-off decision is a negotiating process not generally codifiable.

In addition, individuals who are networked together may not interact as expected (or desired) since flow of information is strongly influenced by those in control of the information [65], [84]. Thus, patterns of communication and data transfer are extremely difficult to model (and predict), especially when the artifact (such as the project) is extremely complex. As a result, the assumption of codifying the design process, particularly in the ill-defined conceptual stages, is currently implausible. Only well-defined problems or nearly independent processes are candidates for CE tools.

### **C. Assumptions About Human-Computer Interaction**

The last two assumptions emphasize designers interacting with computer interfaces rather than traditional means of information exchange such as drafting boards, written manuals, and meetings.

#### **Assumption #8: Well understood principles of enhancing human-computer interaction (HCI) exist.**

CE tool developers recognize that a successful tool must provide a consistent interface for communicating and manipulating information among all team members [10]. For example, the Intelligent Design System (IDS) uses interactive processing which warns a designer of problems and sorts all options to resolve problems by priority in order to avoid the need for on-line manuals to guide diagnosis [14]. The IDS technology includes a comprehensive aid scheme, a data and information controller, and a number of applications. Another example is the Design Fusion project which had as an objective to coordinate the group problem-solving activity of multiple perspectives [27]. The designer is provided an interactive environment through which specifications and constraints are set, libraries of existing designs are accessible, and designs can be modified. The CE tool developers for the Design Fusion Project intended a designer to interactively participate on-line in the design by evaluating and critiquing ongoing designs in any of the available (design) perspectives.

In both of these CE tool development cases, little effort was devoted to designing the human-computer interface; the current state of HCI was assumed to provide professionally-accepted design principles for supporting cooperative problem solving which could be readily integrated into the CE tool.

#### **Plausibility Assessment of Assumption #8**

While some principles of HCI are well-understood, those that have to do with facilitating collaboration are not well-understood since more than a user-friendly interface is needed [33]. CE tools integrate communication technologies, cooperative work tools, intelligent databases, advanced design tools and other technology-driven functionalities with system (engineering) design principles. Each of these elements have HCI stumbling blocks that are documented in the literature. These stumbling blocks include the need for an interface to adjust to different interface styles and experience levels of users, and to different task characteristics. Well-accepted HCI principles for overcoming

these stumbling blocks have yet to be developed.

The HCI of computer-mediated technology that involves multiple-user or group interfaces has only recently been addressed [22], [30], [32]. A review of empirical research on electronic technology in work groups often found conflicting results [49]. Some of the contributing factors were differences in spatial distribution of group members, temporal distribution of group activities, and variation in task type. For example, Aiken et al [2] studied group decision support system sessions and found that user interfaces, group communication, and access to information all require human expertise to correct. In another study on group support systems, task type was shown to be such an important variable in predicting the effectiveness of computer-aided decision support that different support systems might be needed for different types of group tasks [72]. There are also unresolved issues of cooperative design including "articulating" cooperative work, sharing an information space, and adapting the technology to the organization [5]. These issues do not as yet have clearly articulated HCI design principles. As a result, CE tool developers will find themselves charting new waters in data protocols and computer-mediated collaboration making this assumption implausible. CE tool developers will have greater success when focusing upon a specific set of problem solving conditions.

**Assumption #9: Existing user interface technology is sufficient to adapt to individual differences in tool use and designer styles.**

Since CE involves many different individuals from different disciplines using a variety of problem-solving approaches, CE tools must be able to allow for, and interpret, these differences. CE tools are seen as doing this in a "natural interactive collaboration environment by integrating voice, gestures, and shared views of the engineering design which accommodates different user preferences that reflect the detail in the presentation of information" [15, p.53]. The IDS uses "functional envelopes", which present a cognitive work analysis of the designer's work domain and strategies in problem solving, thereby permitting the user to switch between procedures according to personal preference [14]. User interface technologies, such as adaptive interfaces, are therefore assumed to be capable of making CE tools adaptable to any individual or problem-solving style. And again, CE tool developers assume that current HCI provides professionally-accepted design principles for adaptive interfaces.

### **Plausibility Assessment of Assumption #9**

CAD tools that emphasize geometric representations are the technology used most often by existing CE tools. Thus, if difficulties have been encountered in accommodating to individual differences in the use of CAD, then these difficulties should be a warning for CE tool developers. And difficulties have been encountered in adopting CAD use to individual differences [1], [47]. For example, Sinclair [68] found in his study of CAD users a need to support users who made design decisions in different ways: some wanted detail while some wanted only conceptual knowledge. Other types of individual differences in decision making styles [9], [18], sub-discipline perspectives [36], values and goal preferences in decision making [81], and communication styles [28] have been identified as well.

One way in which CAD user interfaces have been designed to accommodate to these individual differences is to present semantic information in varying levels of detail as additions to illustrations of design objects [34]. The nature of these semantics depend on a dialogue flow and language of communication which can be different for each user [13].

Apparently from the experience with CAD, a balance has to be struck between the technological standardization imposed by a computer-based tool, the variety of ways in which a particular problem can be solved, and the individual preferences of the problem-solver [83]. This balance becomes even more complex when the design activity involves users from more than one discipline, each using their own highly specialized engineering tools and each trying to make their data available to non-specialists from other functions.

Thus, if CE tool developers choose not to account for, and accommodate to, these individual differences, one inevitable and historical outcome is that users will again be required to adapt to the computer by adjusting their skills, knowledge and personal work process to the CE tool. A user wants to concentrate on the task to be accomplished and not the technology itself. Forcing the designer to adapt to a standardized modus operandi, particularly with work that is largely non-standard, is likely to rob the product of the essential creative element in the design process. Moreover, forcing standardization is unlikely to succeed. For example, the difficulties that large corporations have in standardizing on a particular spreadsheet or word processor is an example of the demand for different user preferences even in a narrow software application domain. This assumption is therefore

implausible given the research nature of existing HCI technologies.

Table 2 - Summary of Results from other Technologies

Assumption	CE Tool Technologies	Results from other technologies
<b>Lateral Coordination</b>		
1. † An integrated computing environment is sufficient for information sharing to occur	Communication networks; linked databases	Unexpected changes in communication patterns and organizational interaction
2. ‡ There is a single representation of key design features that is understandable to the entire design community.	Data standards; knowledge translation	A physical (geometric) representation represents the needs of only selected members of the design community
3. † CE tools can support the interaction of multi-disciplinary teams.	Group decision support; negotiation and conflict management	Unpredictable team interaction; inability to reconcile multiple-dimension views; organizational resistance
4. † Linking remote designers using a CE tool can substitute for physical co-location.	Communication; CSCW	Proximity aids cooperation; visible interaction needed in design activities
<b>Data Needs of Designers</b>		
5. ‡ A designer needs and wants access to all information relevant to a design.	Interoperable databases and tools; translators; knowledge representation	Experts search for the minimum amount of information; good coordination requires less information
6. † Primary type of information used in design is digitally representable and context free.	Data standards; knowledge representation; multi-media	Lack of agreement on standard representation; difficulty in representing tacit knowledge from many unique design domains
7. † Design process can be codified resulting in opportunities to intelligently aid design (synthesis) activities.	Models of design process, cognition, collaboration	Design process is poorly understood; many of processes are non-analytical and ill-defined
<b>Human-Computer Interaction</b>		
8. ‡ Well understood principles of enhancing HCI exists in cooperative problem solving.	User interfaces; CSCW	Unexpected group dynamics and social issues
9. ‡ Existing user interface technology is sufficient to adapt to individual differences in tool use and designer styles.	Adaptive interface, decision-support tools, HCI	User interfaces unable to accommodate wide variety of designer styles and differences in problem-solving approaches

‡ - inconsistent with literature

† - limited support in literature

## IV. SUMMARY AND CONCLUSIONS

All of the nine CE tool developers' assumptions identified in the twenty CE tool development cases are inconsistent with documented behaviors identified from related technology developments. A summary of the plausibility of these assumptions is shown in Table 2 indicating that four of the assumptions were completely inconsistent with documented experience of other technologies and the remaining five assumptions were partially inconsistent with documented experience. Given the implausibility of so many human factors assumptions, what should CE tool designers do?

First, we believe there is sufficient evidence from implementation experiences in related computer-based technologies to restate the assumptions (Table 3) to reflect the impact of humans and organizations in facilitating multi-disciplinary design. Given these restated assumptions, the CE tool community needs to develop strategies for creating tools that refocus their development work on the restated assumptions. While there may be many strategies, we recommend three complementary strategies.

- 1) *Develop CE tools based on principles of user-centered design;*
- 2) *Develop components for CE tools (such as wrappers) that capture information on the contextual realities in which the CE tool is being used and use this contextual information to modify the tool to the needs of the user; and*
- 3) *Develop CE tools differently when they are used for early conceptual design than for later detailed design.*

### Strategy #1: CE Tool Developers Should Follow a User-centered System Development Process

A system development process, called “user-centered design” recommended by Eason [21] and others (e.g., [52]), follows a system specifications process that is different from traditional requirements definition in the following ways:

- System specifications are created during an iterative, rapid prototyping process with users.
- System specifications are not limited to the technical system; specifications for a high-performance social system are included as well, which means that system specifications may include specifications for a reengineered business process (such as workflow), upgraded workers' skills, redesigned jobs (e.g., “jobs should carry attributable responsibility for outcomes”, “jobs should provide for a variety of tasks”), and redesigned reporting hierarchies

and coordination procedures.

- System specifications are based on a form of cost-benefit assessment, process mapping, user population mapping, and user reaction assessments performed separately for the different groups of stakeholders so that different perspectives on the proposed system can be made explicit.
- System specifications are constructed using a structured procedure called “Open Systems Task Analysis” which models the primary purpose of the sociotechnical system and its inputs, environment, transformations, and role expectations of all parties.
- Criteria for evaluating the sociotechnical system include not just cost and productivity, but future learning/growth potential, organizational effectiveness, and health and welfare of users.

Once a set of agreed-upon system specifications (based on a series of ever-evolving prototypes) have evolved, a pilot system design and field trials are conducted to provide feedback about the specifications. An evolutionary path is then undertaken in which an operational system is designed, implemented, used, evaluated, and then refined. In this system-building process, users are not merely “involved” by asking them for their requirements, but the organizational system itself becomes part of the focus of the design. The "user-centered" design approach is well suited to organizations that commit to change over several design cycles. A typical CE organization evolves during each design process cycle requiring the CE tool to provide new features to meet a new level of concurrent design knowledge.

This strategy of a user-centered CE tool development process would promote the effective application of many of the restated assumptions by providing the context-specific understanding for the particular setting in which the tool would be used. Using assumption #1 as an example, the role of users' semantics and preferences on information-sharing would be better understood prior to CE tool design so that design criteria could be developed that align with those semantics. Similarly, such a process would help significantly in applying assumption #9 by identifying the precise balance between minimal critical specifications for a standardized interface versus flexibility for user modification.

Table 3 - Restated Assumptions based upon Literature

Original Assumption	Restated Assumption	Applications to CE tool design
<b>Lateral Coordination</b>		
1. An integrated computing environment is sufficient for information sharing to occur	Information-sharing will occur with a computing environment that integrates technology, (data) architecture, semantics, and allows user to focus on tasks - not computing technology.	Semantics and users are better integrated into a CE tool when design processes are understood and congruent organizational design features exist. Need clear goals and guidance on which interactions occur in design process.
2. There is a single representation of key design features that is understandable to the entire design community.	Representations based on explicit cognitive models are needed so an entire design community can understand key design features vis-a-vis the explicit model.	A single representation is sufficient when cognitively similar activities are involved (e.g., metal fabrication). Products that include mechanical, electrical, and (computer) processing elements require multiple representations. These should have explicit cognitive models drawn and overlaps between them described.
3. CE tools can support the interaction of multi-disciplinary teams.	Tools will support interaction of multi-disciplinary teams only when interaction is supported by organizational structure, culture, training and experience.	Tool design incorporates social and organizational constraints (e.g., e-mail with rules of engagement and management checkoffs) coupled with an implementation plan that outlines needed changes to organization.
4. Linkage of remote designers with a CE tool substitutes for their physical co-location .	Once designers have established communication norms, remote linkage of CE tools can substitute for context-free data exchanges.	Team-building and negotiation of critical design issues in face-to-face setting is prerequisite for utilizing remote communication methods. Consider checklist of prerequisites before remote usage.
<b>Data Needs of Designers</b>		
5. A designer needs and wants access to all information relevant to a design.	Designers need to quickly focus their search to relevant design information and be guided through the proper interpretation of relevant design information not within their discipline	Designers have to be shown crucial boundaries where external information is needed so that cognitive overload is avoided; guidance for interpreting information; and guidance on reducing information search efforts

Original Assumption	Restated Assumption	Applications to CE tool design
6. Primary type of information used in design is digitally representable and context free.	Design information is a mixture of prescriptive, tacit and context-specific data.	Tools are suitable for prescriptive analysis (mathematical and algorithmic aspects). Information should be presented in a way to facilitate user's tacit and context specific data (such as through queries).
7. The process of doing design work can be codified resulting in opportunities to intelligently aid design (synthesis) activities.	Design process is most easily codified when tasks have minimum inter-dependencies.	Design process must be thoroughly understood before sequencing of process is automated. Many sources of variations in processes have to be considered as task interdependence (e.g., multiple disciplines) and product complexity increase.
Human-Computer Interaction		
8. Well understood principles of enhancing HCI exists in cooperative problem solving.	HCI principles of effective collaborative problem-solving are highly contingent upon task type and social factors	Treat human-computer and computer-mediated collaboration separately. For collaborative problem solving, design interfaces to enhance reasoning process, participation according to knowledge and reinforcing informational influence.
9. Existing user interface technology is sufficient to adapt to individual differences in tool use and designer styles.	Balance needs to be struck between degrees of standardization and individual preferences of users	Identify minimal critical specifications that can be standardized; allow user to modify all others

Strategy #2: CE Tool Developers Should Design A Human Factor Component in Their Tools

As the second strategy for CE tool development, we recommend that a CE-tool component should be developed that integrates human aspects of design with the technical elements. Since many CE tool developers use software "wrappers" to translate design data passing between disciplines, it would be logical to enhance the capability of a wrapper to allow for human factors. Given the documented behaviors found in the literature for each assumption, a component for a CE tool such as a wrapper that adequately incorporates human factors issues would have the following characteristics:

- As restated in assumptions #1 and #2, an integrated computing environment involves sharing cognitive models as well as technologies to accommodate the different perspectives that team members bring to a CE design process. Therefore, the wrapper should include a mechanism for sharing and exploring each CE team member's cognitive model, an automated (e.g., machine-learning) ability to devise "meta-cognitive models" that integrate or at least connects the different cognitive models, and a mechanism for sharing and using the meta-cognitive models in information exchange and interpretation which is a means of integrating semantics [16].
- As restated in assumption #3, CE team members are likely to represent different functional and professional interests, and thus their interaction needs to be supported by organization as well as technology enablers. Therefore a wrapper should include a mechanism for CE team members to interact in ways that help protect their different interests and find common solutions and information-sharing strategies. Such a mechanism might incorporate principles learned from negotiation and "win-win" game-playing into heuristics for guiding information-sharing and computer conferencing. For example, the CE tool could be developed to provide early identification of the likely impact of a variety of performance criteria of design solutions being considered individually by each team member and then broadcast those assessments to the team with a message like "it's time to weight these different criteria since they all are unlikely to be met".
- Typically, constraints on CE tool use are built into the basic structure of the CE tool; as discussed in assumption #7, this practice tends to perpetuate status differences among team members. Thus, to eliminate status differences, the wrapper should allow the CE team, at the outset, to establish the constraints for file access, file modification, information-sharing to whom about what, and appropriate computer configurations for using the CE tool. To prevent data security problems, those rules could only be modifiable when all team members provide a digital "signature" agreeing on the change.
- Because, as restated in assumption #5, CE team members need guidance on how to access only specifically relevant information, a wrapper should help determine what information is needed by "prompting" users about additional activities they might consider, other functions to query for information, and potential problem-solving strategies.
- As restated in assumption #2, since there is unlikely to be a single representation for all design perspectives, the wrapper should identify vector diagrams or clusters of common representations and make these overlaps and non-overlaps apparent to the users both at the outset of starting a team and as the team evolves.
- Since, as restated in assumption #6 that the technical specialization among CE team members creates a dependence of each member on each other to correctly interpret their own data, the wrapper needs to provide a means for CE team members to ensure that each of them is in fact interpreting data in a way that meets the expectations of others. Some techniques include data exchange templates, change notification with different thresholds of action, messages indicating criticality of data, and mappings of intended utilization and potential interaction. A practice design case of data which is reviewed and interpreted by all CE team members at the outset of a CE design process and intended utilities becomes the testbed for negotiating the boundaries and power of the wrapper. Differences in data interpretation could then be sorted out with this practice case prior to people becoming so personally involved in their data that they become less open to accepting alternative interpretations of the data.

- Given, as restated in assumption #5, that CE designers do not want all information but only problem-specific information that cannot always be identified in advance of a design effort, the wrapper needs to allow users to suggest and modify at any time rules for the automatic retrieval of information. For example, a designer may initially think that she wants the CE tool to automatically inform her every time a design alternative is likely to exceed \$X costs. Later on in the design process as she gains a better understanding of her design problem, she may be able to pinpoint the likely cost drivers (that could, for example, include a need for too much technical flexibility among the workforce likely to be working with her product) and then ask that the CE tool automatically inform her when impacts to flexibility among the user community is likely to be too high.

### Strategy #3: CE Tool Developers Should Develop Different Tools for Early versus Later Design Stages.

In addition to the development of CE tool wrappers, our analysis supports the notion that CE tools will need to be designed differently when supporting a CE design process that is at the early, highly innovative and unpredictable conceptual design stage versus later stages in which more routine design implementation is being undertaken. A tool that facilitates conceptual design is likely to be one that assumes and supports physically co-located designers (assumption #4); thus the tool does not need to provide a functionality for multi-media transfer of ill-conceived ideas since this can be done manually. A tool for conceptual design should encourage information-sharing by suggesting sharing of ideas to appropriate people at the close-out of each session, rather than demanding it using a standardized project management PERT chart (assumption #7). In addition, if such a tool were to have the capability of automatically highlighting the latest revisions to a design, and allowing the user to accept or override rule-based recommendations about what kind of feedback she wants from whom by when and in what form (verbal, drawing changes, analytic results), then the necessary coordination is facilitated and not forced. A tool for conceptual design is concerned with an unpredictable design process; as such, data exchange protocols for tools supporting conceptual design will probably be limited to only decisions and data having known and distinctive overlaps between functions (such as tolerance information having known utility to design, manufacturing, marketing, and procurement) (assumption #1). Finally, a tool for conceptual design should facilitate the evolution of a common language among the CE team members by performing ongoing automated semantic analyses of

inputted text to identify common and different uses of similar words (assumption #1).

In contrast, a tool that facilitates later stages in the CE design process is one that should first, provide a mechanism for bringing new team members up to speed quickly by providing the necessary documentation as to why certain design decisions were made, dictionaries of language-use, and agreed-upon norms and procedures of the existing CE team. Such a tool should also build into the interaction between users and the tool (with user override of course) the procedures agreed upon by the team for coordination so that the users need not personally carry out the procedures (e.g., once a finite element analysis is completed, the results should be automatically reported to the mechanical engineer). The tool should facilitate global virtual co-location by providing clocks on the screen of the local times of the various team members, having a schedule of how and when to reach the various team members, and provide an automated rotation for team teleconference calls so that all team members equally share the burden of global participation. The tool should provide data bases for standards-checking and allow these to be turned on and off at will by the user; when a standard is not met, have the system automatically (with user override of course) inform the team member(s) responsible for meeting those standards and suggest alternative ways to meet the standards. Finally, the tool should include standardized data exchange protocols since this is a stage in which the design activities are better understood and relationships among design decisions are modelable.

Developing different CE tools for early versus later stages in the design process will then help to effectively apply the restated human factors assumptions. Since the work, human, and organizational activities of the different stages in the design process are so different, it is perhaps not surprising that different tools should be needed.

In sum, our analysis suggests that CE tool developers may, in all probability, be on a development trajectory in which the CE tools will be underutilized and with as much pain and difficulty as experienced by other innovative, computer-based technology developments. Stopping to look at the human factors issues early on in the development process may help to avoid some of this pain.

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