Characterizing Distributed Concurrent Engineering Teams: A Descriptive Framework for Aerospace Concurrent Engineering Design Teams

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As aerospace missions grow larger and more technically complex in the face of ever tighter budgets, it will become increasingly important to use concurrent engineering methods in the development of early conceptual designs because of their ability to facilitate rapid assessments and trades in a cost-efficient manner. To successfully accomplish these complex missions with limited funding, it is also essential to effectively leverage the strengths of individuals and teams across government, industry, academia, and international agencies by increased cooperation between organizations. As a result, the existing concurrent engineering teams will need to increasingly engage in distributed collaborative concurrent design. This paper is an extension of a recent white paper written by the Concurrent Engineering Working Group, which details the unique challenges of distributed collaborative concurrent engineering. This paper includes a short history of aerospace concurrent engineering, and defines the terms 'concurrent', 'collaborative' and 'distributed' in the context of aerospace concurrent engineering. In addition, a model for the levels of complexity of concurrent engineering teams is presented to provide a way to conceptualize information and data flow within these types of teams.

Nomenclature

CE = Concurrent Engineering
CET = Concurrent Engineering Team
CML = Concept Maturity Level

I. Introduction

The term *Concurrent Engineering* is used in different engineering disciplines to mean different things, but in the aerospace domain the usage of the term is reflected in the following definition:

> Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including, manufacturing and support. This approach is intended to cause the developers from the very outset to consider all elements of the product life cycle, from conception to disposal, including cost, schedule, quality and user requirements.[1]

Concurrent engineering was first applied to space mission concepts by NASA's Jet Propulsion Laboratory in 1995, as a response to the then "faster, better, cheaper" challenge within NASA. By collocating the scientists and spacecraft design engineers in order to conduct design work concurrently, design issues that arose could be collaboratively resolved in real time. This significantly reduced the communication pitfalls of a traditional design team that relies on a physically distributed team that only meets at periodic status meetings. In the sixteen years since then, concurrent engineering teams have evolved their methods, tools and facilities such that conceptual designs can now be completed in a fraction of the time and cost needed to do the same using the traditional distributed team. Several aerospace organizations around the world now have concurrent engineering teams in order to facilitate rapid trades of performance, cost and schedule. As aerospace missions grow larger and more technically complex in an era of even tighter budgets, multi organizational partnerships will become increasingly necessary –

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and with it, the need to leverage the strengths of individuals and teams across government, industry, academia, and international agencies. As a result, the existing concurrent engineering teams will need to increasingly engage in distributed collaborative concurrent design, in which two or more concurrent engineering teams in geographically distant locations collaborate on design projects. While attempts have been made in the past to conduct distributed collaborative design with multiple concurrent engineering teams, these attempts have not been fully successful. The challenges faced in these collaborations indicate that a better understanding of the characteristics of the teams is needed in order to efficiently leverage the strengths of each team and design the connections/interactions between the teams.

II. Definitions

A primary differentiator between different types of engineering design teams is the degree of concurrency and collaboration in the team, which are not necessarily the same thing. In engineering literature, the terms 'collaborative' and 'concurrent' have often been used interchangeably in the past. However, in this paper, they are defined distinctly as:

Collaborative - A collaborative design team is composed of people working in an integrated setting, exchanginginformation and making decisions jointly, and cooperatively producing and refining a design.

Concurrent - A concurrent design team is a team that works collaboratively with low response latency. In a concurrent design team, integrated tools enable real-time data exchange enabling rapid design changes.

Distributed - A "distributed" collaborative or concurrent design team includes geographically distributed teams or team members. Most aerospace concurrent engineering teams work in a co-located setting, enabling rapid dynamic interaction on the human-level supported by a set of integrated tools with managed parameter definitions. Most existing single concurrent engineering teams have at least limited experience with distributed collaborative interaction, in which one or two customers or subject-matter experts interact with the team via teleconference. However, in distributed collaborative engineering teams, two or more teams at different geographical locations will interact via teleconference as well as possibly linked tools.

III. Aerospace Engineering Design Teams : Design Team Framework

As a first step in characterizing concurrent engineering teams, a taxonomy of teams based on their salient attributes is proposed. A framework is proposed, consisting of a set of team variables, team attributes and study attributes that will enable the comparison of different type of aerospace engineering design teams. In the following sections, we describe the framework components, and then use these components to define the range of aerospace engineering team structures from traditional design teams to fully distributed concurrent design teams. This framework will allow us to then describe the behavior of these types of teams in various settings. This leads to the identification of the strengths and weaknesses of collaborations between different types of teams by enabling one to infer the characteristics and performance of resulting collaboration.

Teams are characterized through the use of Concurrent Engineering Team (CET) Variables -- descriptive characteristics of the team that affect the overall performance of the team. These variables are 'measured' on a relative scale and, along with external study conditions, can be used to predict the team's performance in a particular study. The overall objective of a design study is to minimize the study cost and latency, while maximizing fidelity. Understanding the CET Variables and performance characteristics of single teams provides a means to anticipate the attributes of a distributed team created through the collaboration of those single teams.

A. Concurrent Engineering Team (CET) Variables

The CET variables are design choices that can be made during the team's development, or aspects of the team that can be adjusted to affect the team performance. These are not necessarily independent variables, but are rather different salient aspects of the team that can be used as a baseline list to characterize and differentiate the different types of engineering design teams.

Number and Type of Links

Within a single engineering design team, there are two different ways in which information is transferred between the participants – information links, in which information is passed verbally through conversations between team members, and data links, in which parameters are passed electronically between linked tools. A team that has no connected tools only shares information through verbal links. Information links allow team members to discuss issues, and create a shared design lexicon and context. Information links may also engender closer relationships between team members, which help build trust within the team -- essential for efficient collaboration. Concurrent engineering teams that have evolved to include connected tools utilize a mixture of verbal links and data links. Data links may enhance the local situational awareness of each team member by providing visibility into shared parameters, thereby reducing confusion about parameter values. While in general more links are better than fewer, too many links may be detrimental to the team design activity by causing information overload for team members. It is challenge to optimize the combination of information and data links. Both types of links are valuable for a high performing design team, and teams that focus only on one or the other type of link lose capability.

The optimal combination of data and information links for a team also depends on the type of team, and their objectives. For teams dealing with lower fidelity designs, having mostly verbal links is sufficient, and linking tools may not add much value as there are few shared parameters that affect all of the team members at the subsystem level. However, if there is a large team and a high fidelity design with a large number of parameters to track, there is a need for more data links in addition to verbal links.

Geographical Distribution

The initial new feature of a concurrent engineering team compared to the traditional design team was the collocation of the design engineers during much of the design process. Collocation facilitates easier communication, and thus faster resolution of design conflicts. Collocation also enables the team to uncover design inconsistencies more rapidly than in the traditional paradigm, where communication between team members is sporadic and inconsistencies are generally only visible at the system level. Collocation also fosters better teaming, as face-to-face interactions lead to the development of better relationships between team members.

However, being able to accommodate geographically distant team members is a capability that many currently operating CE teams have developed. Often, the customer or a subject matter expert is engaged remotely while the core CE team is collocated in a room. Geographical distribution introduces limitations on the number and type of links that can be supported with the remote team member, and hence may diminish the performance of the concurrent engineering team. Currently teams almost exclusively support only information links with remote participants – such as teleconference links with a remote customer. While utilizing geographically distributed team members or diverse distributed teams in distributed collaborative participation is the future of concurrent engineering, it is important to consider the ramifications of introducing more extensive remote participation. By definition, in a geographically distributed team, the advantages of collocation, one of the primary benefits of concurrent engineering, are lost. While observing remote participation in a geographically distributed engineering team, Mark and Abrams reported that the introduction of remote links hampers spontaneous communication:

> A major risk for large-scale scientific collaborations is when perspectives are not questioned. At local sites, spontaneous challenges to design parameters and assumptions and debate and negotiation were the norm. In contrast, we rarely observed spontaneous challenges made by team members across distance.[2]

However, geographical distribution does enable teams to leverage external experts, or engage another concurrent engineering team that brings in its own expertise – so the trade between the value gained by engaging remote participants and teams and the reduction in performance of the team due to geographical distribution must be carefully considered.

Team Size

As every engineer has experienced, a larger team size leads to less effective collaboration. There is a limit to how many collaborators a team member can effectively engage with during a design session. Larger team size means that each team member has to support a larger number of links concurrently, which makes it difficult to complete their own tasks simultaneously. It is also more difficult to maintain situational awareness across a large team, as disseminating information across all of the members is difficult and time consuming. If situational awareness is low in the team, significant time can be squandered trying to uncover and resolve inconsistencies in design assumptions. The problems associated with large teams are magnified in the case of collaborations between distributed teams, as the team members now have to support links across the teams in addition to the many links within their own team.

Infrastructure and Tools

A concurrent engineering team requires facilities for the team meetings, as well as other technology to support interaction and links. Different infrastructure and tools are appropriate for different concurrent engineering activities – a concurrent engineering team primarily engaged in brain storming architecture trades may only require stand-alone, unlinked tools to adapt to different architecture assessments, and mostly utilizes a simple white board, whereas a team assessing a point design with linked tools will need a more elaborate set up with networked machines and several displays. See Ref. 3 for a more detailed discussion of concurrent engineering team infrastructure and tools.

For a concurrent engineering team, the size of the room in which they meet also matters. Typically, in a smaller room, people interact more. Through experience, the arrangement of the concurrent engineering facilities have evolved such that the team members who need to interact with each other the most are located relatively close to one another. This fosters frequent communication.

Range of CML

One useful way of differentiating the design teams is by looking at the maturity of the concepts that they assess. Concept Maturity Level (CML) is a recently created measure for assessing the maturity of an evolving concept (see Ref 4 and in the Appendix). For example, a team that primarily deals with point designs is likely to work on CML 4 and beyond designs, while an architecture comparison team deals with CML 3 or earlier concepts. A team is typically developed for the purpose of assessing a particular CML range, as a concurrent engineering team needs very different infrastructure, tools, and processes to deal with each CML. It is very challenging to make a single team-type fit all concept levels. The type of products the team generates -- whether it be a higher-level architecture comparison, or an elaborate point design – is also a result of this choice of CML range.

B. Concurrent Engineering Team (CET) Attributes

The choice of CET variables for a team results in the particular team performance characteristics – denoted here as "attributes" – for the team. These CET attributes indicate the behavior of the teams in a typical design study. Changing the CET variables may change the resulting attributes. The three primary attributes of a CET are Flexibility, Teaming and Situational Awareness. These attributes are discussed in more detail below.

Flexibility

In the context of an engineering design team, the flexibility of the team refers to its ability to respond to external changes, including changes to the assumptions of the design, as well as changes to the process and products of the team based on changing customer needs.

At the start of an engineering design, certain assumptions are defined in order to scope the design effort and set the boundaries of the design. A team with operational flexibility has a process capable of accommodating changes to those initial assumptions (within certain bounds), without significant impact to the end design product accuracy and fidelity, or the design timeline. Teams that are collaborative, with many information links between the teams are able to disseminate the change information across the team quickly. However, if the processes and tools that the team uses are optimized for a small subset of the design tradespace, it is unlikely that the team will be able to easily and quickly adapt the process and tools to respond to the external changes. Most concurrent engineering teams have standard design products that they provide to the customer. Specific customers may desire customized products - this may be difficult for a team with lower flexibility due to automated product generation processes. Fewer automated processes, and unlinked tools may make a team more flexible, however, this flexibility must be balanced with the other CET attributes which benefit from automated processes and linked tools.

Teaming

Teaming involves all aspects of team behavior that enable effective collaboration in a high performing team. Teaming is affected by the geographical distribution of the team, as well as team size. Collocation facilitates team cohesion by enabling the development of a shared identity and common language. A high performing team has a shared context and trust among the members, which enables them to question design assumptions and resolve issues quickly. Such a team also allows for shared leadership based on changing needs, as is seen in concurrent engineering teams when subsystem chairs take the lead to resolve system issues that relate to their subsystem. Trust and good communication within the team allows for emergent conversations to identify and resolve design issues early in the process. Information links between team members results in a high level of teaming in smaller teams. In larger teams, additional data links are required in order to propagate information, but relying primarily on data links reduces communication in the team and reduces performance.

Situational Awareness

Situational Awareness (SA) is defined as "keeping track of what is going on around you in a complex, dynamic environment"[5]. As discussed in Ref. 3, maintaining situational awareness is a key concern in concurrent engineering environments. Typically, the larger the team, the more challenging it is to maintain SA. Teams with linked tools can have increased SA as they can share design parameters through linked tools, reducing the possibility of design inconsistency. However, being reliant only on data links, with minimal verbal links reduces the amount of discussion between team members, which decreases situational awareness. Communication in a geographically distributed state, even with advanced teleconferencing tools, is challenging :

> Distributed design teams make decisions as geographically dispersed members interact via various telecommunications mediums (video conferencing, software interfaces, etc.). Interaction through such mediums has been shown to alter the nature of communication and limit the capacity of interaction within the group.[6]

Concurrent engineering teams utilize various methods to maintain SA, including periodically reviewing the design assumptions, using consistent data definitions, and setting up the team facility such that chairs for closely related subsystems are located near each other to facilitate communication. Situational Awareness is improved by infrastructure that allows for easy displaying of information to the team, and being able to changing screen displays quickly, or by limiting the number of external links to geographically distributed members.

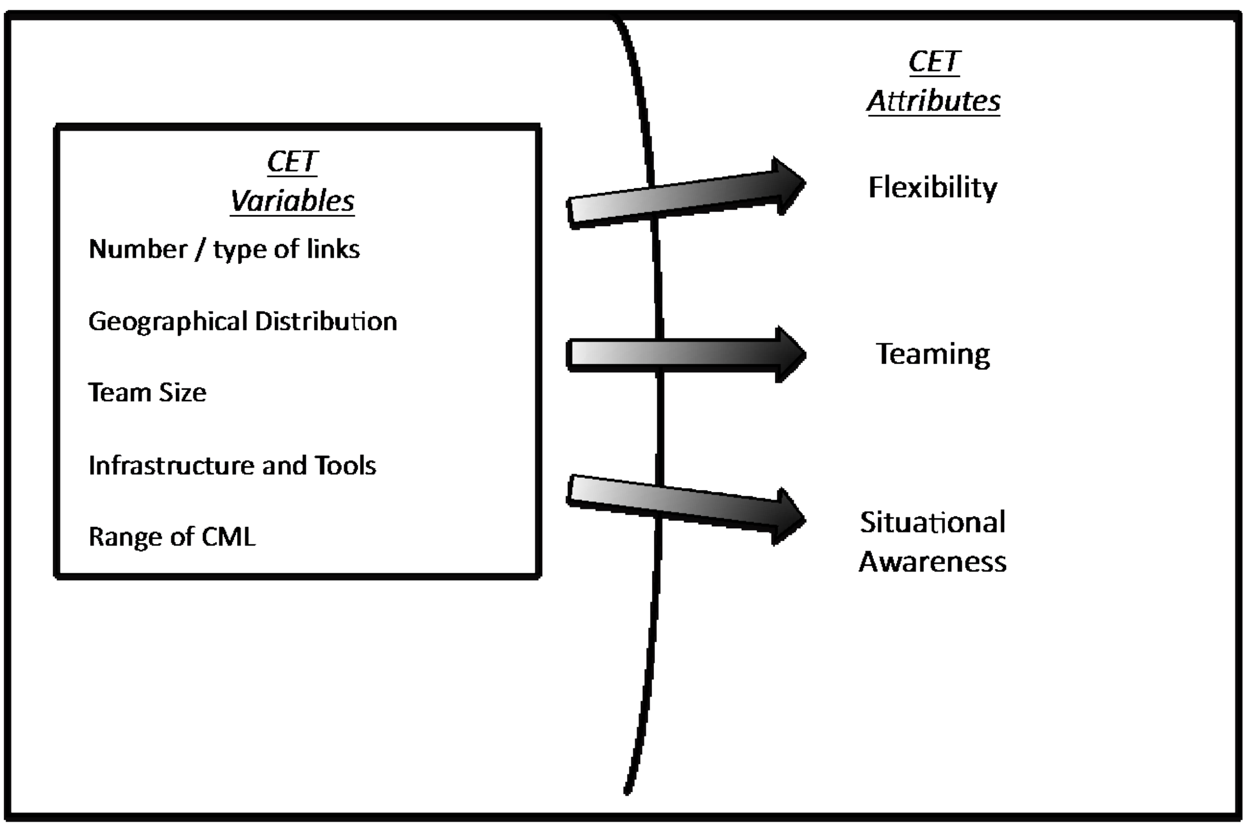

Figure 1: Relationship of CET variables to attributes

C. Engineering Design Study Attributes

The original purpose of applying concurrent engineering methods to aerospace conceptual design was to enable "faster, better and cheaper" design. In terms of how design teams are evaluated, this is interpreted as the Study

Attributes of Fidelity, Latency and Cost (see Fig 2). These three dimensions can be used as to assess the performance of a team in a particular design study. These three attributes are integrally linked, such that picking any two of those constraints will drive the third. This applies to both single teams, and distributed teams. In further development of concurrent engineering teams, the desire is to be able to anticipate the trade-offs between these three constraints for the team, and be able to plan accordingly.

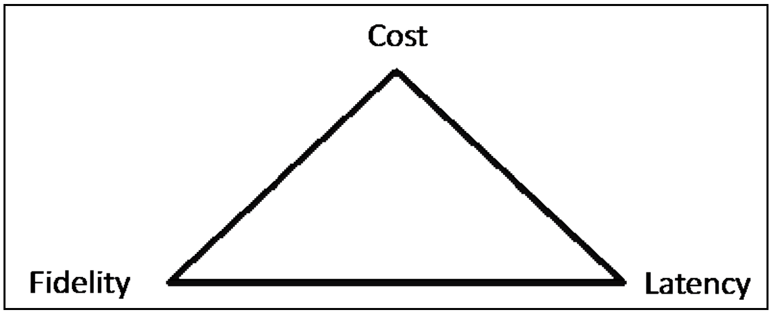

Figure 2: Concurrent Engineering Study Dimensions

Fidelity

Fidelity of the design product produced by the team best represents the 'quality' of the design. There are two aspects to quality of the design in the context of concurrent engineering team – accuracy, and fidelity. The fidelity of a model is how closely it resembles the actual system, while accuracy is the correctness of the estimate within a certain threshold. The fidelity of an engineering design increases along the design lifecycle. The models that concurrent engineering teams utilize, and the expertise of team members that participate, are selected such that they generate designs with a certain level of acceptable accuracy for the type of missions that the team is expected to design. This is part of the initial design of the team. Thus accuracy is not considered an attribute – as it is assumed that a concurrent team would develop or gather validated tools with the desired design accuracy. The level of design detail, in other words, the fidelity of the design that is produced by a team is what may change, based on the study assumptions, capabilities of the tools, and the time available for the design study.

The fidelity of the design product varies from team to team. Generating a high fidelity design requires high fidelity tools, which usually require many inputs in order to model the system. Using high fidelity tools requires the starting concept for the design team to be significantly mature, in order to provide the level of detail needed for the inputs. Not all design studies require high fidelity design products. If the objective is to complete high-level design trades, it may be sufficient to generate low fidelity designs in order to enable the feasibility assessment of several design options in a short period of time. In a concurrent engineering team, the desire is to match the fidelity of the tools to the needs of the design study customer.

The number and types of links needed in teams varies with the level of fidelity of the tools and design products. In teams that generate low fidelity designs, and require correspondingly low fidelity models, verbal links are sufficient to enable collaboration, as these types of models do not require many inputs or parameters exchanged between subsystems. If a team utilizes higher fidelity models, more data links are required in order to share parameters among the team members. However, if one desires a high fidelity product from a team with mostly verbal links, latency is increased – it takes much longer to communicate information and resolve design inconsistencies within the team when a large number of parameters have to be exchanged verbally. This also applies when the team is large, or geographically distributed.

Latency

Latency in a concurrent engineering team is the time needed to come to a design decision after information is requested, or an assumption is changed. Latency affects the time that is needed to develop a feasible design. Latency in a concurrent engineering team is driven by the availability of information. If the information that team members need in order to make key design decisions is readily available, design decisions can be made much faster and issues can be swiftly resolved. Such a team has low latency, and thus can complete design studies to a desired level of fidelity much faster than a team with higher latency.

In addition, when design assumptions change, they must be propagated through the design team so that design decisions are not made based on incorrect information. If a team has linked tools, with many data links, design assumptions and parameters can be propagated quickly and consistently through the team, reducing latency more so than if the team primarily relies on verbal links. Data links are necessary, but not sufficient for low latency in a team – a key component of the rapid engineering decision-making in a team is the verbal links between team members that leads to discussions about design issues.

The infrastructure used by the team also affects the latency in various ways. If the facilities are not well suited to easy access/interaction, this will impact emergent conversations/spontaneous discussion and will increase latency. The speed of information flow within a collocated team is dictated by the arrangement of room - a smaller room forces closer interaction and placing engineers for related subsystems near each other spurs rapid resolution of design issues. Slow network speed and limitations of telecommunications links to geographically distributed team members will adversely affect latency. If the tools are linked, it is key for the infrastructure to support quick manipulation, saving and sharing of data between team members as well.

Engineering design teams with high teaming capability will have lower latency – if the team members are able to communicate well with each other spontaneously, and maintain a shared context, design decisions that involve multiple members of the group can be negotiated much faster. Collocated teams also have lower latency than geographically distributed teams, as the sharing information between geographically distributed team members impedes rapid exchange of information. Collocated teams that do most of their work in the design sessions have processes that enable them to work mostly in parallel, rather than sequentially, which reduces the overall time needed for design completion by also bringing to light significant design issues early in the design process.

Cost

Cost is the cost incurred by an engineering design team to develop a design, not the estimated cost of mission under study. This cost does not include the fixed costs of developing the concurrent engineering team, such as development costs of tools and facilities, but rather, it is the marginal cost of conducting the design study, which primarily includes the charge for the team members' time, and the cost of using the infrastructure for the duration of the study. Typically, the cost of the study is constrained by the customers resources, Hence, 'Pick Two' is in reality 'Pick One' other constraint - either fidelity or latency can be selected as the second of the constrained dimensions in the Cost-Fidelity-Latency triangle.

All concurrent engineering design teams attempt to produce the highest fidelity design with the lowest latency possible and at the lowest cost to develop the design. While CE has provided significant savings compared to traditional teams, there is always a desire to reduce study cost even further. There is always pressure to become more efficient, i.e. you're trying to reduce cost but keep fidelity and low latency. Study costs can be kept low by tailoring the process and products to a particular type of spacecraft mission type, and a particular CML – such CET teams may need to spend more in setting up the team and infrastructure initially, but benefit from the investment in being more efficient during the design study. However, when these teams try to do design studies that are outside their expertise, it requires significant changes to the process and tools, and increases latency and thus cost. Aerospace Engineering Design Team Levels

IV. Engineering Design Team Levels

Aerospace engineering design teams can be categorized into several levels, using the CET Attributes of Flexibility to change, Teaming, and Situational Awareness.

Four levels of teams are introduced below. Levels 1-3 describe single teams, while Level 4 consists of distributed teams.

A. Level 1: Traditional Team

Prior to the use of concurrent engineering methods in aerospace engineering, traditional engineering teams would complete design studies over the span of weeks or months. The team members would work independently using domain-specific tools, and meet occasionally in status meetings to sync the design. This approach was used for all levels of design concepts – from architecture-level trades to highly detailed point designs and is still the method employed by engineering design teams at many organizations. Traditional teams are not concurrent – most of the design work is done outside the meetings. The team member designs are functionally decoupled as much as possible, to enable them to work independently and non-concurrently. Typically a traditional team has few links between members, and those links are informational links rather than data links/parameter exchange. There is no specific facility or infrastructure required – meetings can occur in any conference room.

Flexibility: A traditional design team is not very responsive to rapid changes in system-level assumptions. As the subsystem designers/team members do not interact very often, it is challenging and time-consuming for a traditional team to propagate any assumption changes or new constraints across the subsystems. Within the subsystem, changes can be made easily as there is limited connection between the subsystem designs. A traditional design team is better suited to single, focused point designs as there is a high cost for changing assumptions. If the design trades being studied are at the subsystem level rather than system-wide, a traditional team is suitable, but less so if there are many system impacts of the trades. However, traditional teams are flexible in terms of changing the design processes and methods, as the tools are not typically linked.

Teaming: A traditional multi-disciplinary design team has great difficulty evolving into a high performing team, as there are few links and intermittent interaction between team members. The design tasks are more modularized, allowing team members to stay primarily in their own domain and have limited interactions with the other subsystems or the system-level design. As there is no concurrent design work in a traditional team, there is no need for a deep, shared context – a high-level shared context is sufficient for a functionally decomposed design.

Situational Awareness: As a traditional team only meets occasionally to sync the design, there may easily be a drift in perception of constraints or assumed key parameters between meetings. As team members do not share parameters or interact constantly, it is more difficult to be able to maintain situational awareness.

B. Level 2: Collaborative Single Team

The initial applications of concurrent engineering in aerospace were basically collaborative design teams – where the interfaces between people were formalized, in that collocated engineers did much of the design work, but the tools were independent and not linked. There are more links in a Level 2 team than in the traditional teams, but they are still primarily information links. There is some supporting infrastructure – a room with a specified layout and white boards, typically – but no specific tools or machines are needed. Collaborative teams may utilize remote team members, creating information links using teleconference or screen-sharing tools.

Flexibility: A collaborative single team is more flexible than a traditional team. As much of the design work is done while people are in the same room, there are more information links within the team, and it is easier to change the process or the design assumptions midstream and have the effects ripple through the design in real-time.

Teaming: A collaborative team benefits from more shared context than in the traditional case, as there are more information links, and as most of the work is collocated. This improves the team cohesion and efficiency, especially when the same team members are engaged in many studies and develop relationships and work-sharing heuristics.

Situational Awareness: As there are more information links than in the traditional case, situational awareness improves. As most of the design work is done in the meetings, there is less opportunity for assumptions to drift and become out of sync as well. Teams also use displays to share information and develop shared assumptions.

C. Level 3: Concurrent Single Team

A concurrent single team, typical of existing aerospace concurrent engineering teams, does most of the design work in concurrent sessions with a primarily collocated team. The tools used are linked such that parameters can be passed in real-time, enabling many data links along with the information links that are available to collaborative teams. A concurrent team has many information and data links. Concurrent teams may also have some geographically distributed members, who interface with the concurrent team primarily through information links, though experienced teams may also support limited data links with distributed members.

Flexibility: A concurrent team has high adaptability to changing system assumptions due to being concurrent and collocated, as well as having data links to automatically propagate changes to all the relevant subsystems. However, linked tools do result in some limitations to the type of changes that can be made, e.g., cannot support parameters outsides a certain range, or may be limited to be able to handle only certain types of architectures, whereas a collaborative or traditional team could take advantage of other tool suites as their tools are not linked. Recently there has been significant interest in making the tools in the concurrent teams more modular, using integration software, in order to be able to ‘plug-and-play’ different types of tools. This would improve the flexibility of concurrent teams.

Teaming: As much of the design work in Level 3 concurrent engineering teams is done with a primarily collocated team, the team has the potential to be high-performing. While the teaming is generally high in collocated single teams, it is negatively impacted as the team members become more geographically distributed. Teaming also decreases in a larger team, because it is difficult to develop and maintain relationships if there are a too many team member interactions.

Situational Awareness: SA in a single concurrent team can be high for a primarily collocated team, but begins to decrease overall as team members become geographically distributed. The level of situational awareness impact depends on the nature of the human interfaces being affected – for example, if a configuration engineer who needs to interact with all of the subsystems chairs is remotely located from the primary concurrent engineering team, there will be a significant impact to the design latency and situational awareness. The impact also depends on the type of study being conducted – for a CML 4 point design using well understood assumptions and linked tools, there may be a smaller impact of geographical distribution versus while doing quick architecture trades at low fidelity, when much of the information is exchanged verbally. Other subsystem team members who need to interact with fewer subsystems in order to develop their design may be able to work remotely with less impact to overall latency.

D. Level 4: Distributed Teams

A distributed design team, in the context of concurrent engineering, includes geographically distributed teams or team members. Many existing single CETs have some limited experience with distributed collaborative interaction. Customers or subject matter specialists often interact with a CET from a remote location via teleconference or web-based screen-sharing software. The links between the team and the remote participants are primarily verbal information links. Though some loss of situational awareness is expected when team members are remote, in many cases there is not much effect on the overall team performance when only a few such remote links have to be supported.

In a distributed team involving two or more CETs, the interactions are far more complex. The reason for this is described succinctly in Ref. 2 -

> Large-scale, group-to-group collaboration, which involves entire teams residing at each site, is distinct from the more typically studied distributed teams which have one or a few individuals collaborating from each site. In this collaborative setting, people are interacting in multiple social worlds simultaneously: that of their collocated team, and that of a larger, distributed team, connected across distance.[2]

In a distributed collaborative team, there are multiple stakeholder sets to satisfy - the local stakeholder set of collocated team, and the stakeholder set of the global distributed team. There will be multiple information and data exchanges occurring simultaneously not only within the team, but also between teams. These links between the two teams may involve information exchange (such as verbal discussions) or formal parameter exchange between models. These team interactions may be collaborative – with primarily information links, and significant latency in the exchange. In a distributed concurrent engineering team, the teams would have many information as well as data links to support low-latency, real-time collaboration.

Level 4a: Distributed Collaborative Team

In distributed collaborative teams, two or more CETs are linked by a few information and data links, and not all of the design work is necessarily concurrent. The CETs incorporated in the distributed team may belong to any of the levels 1-3 of CET classification. There may be different levels of collaboration – one example the interaction of two Level 3 teams (Figure 3) .

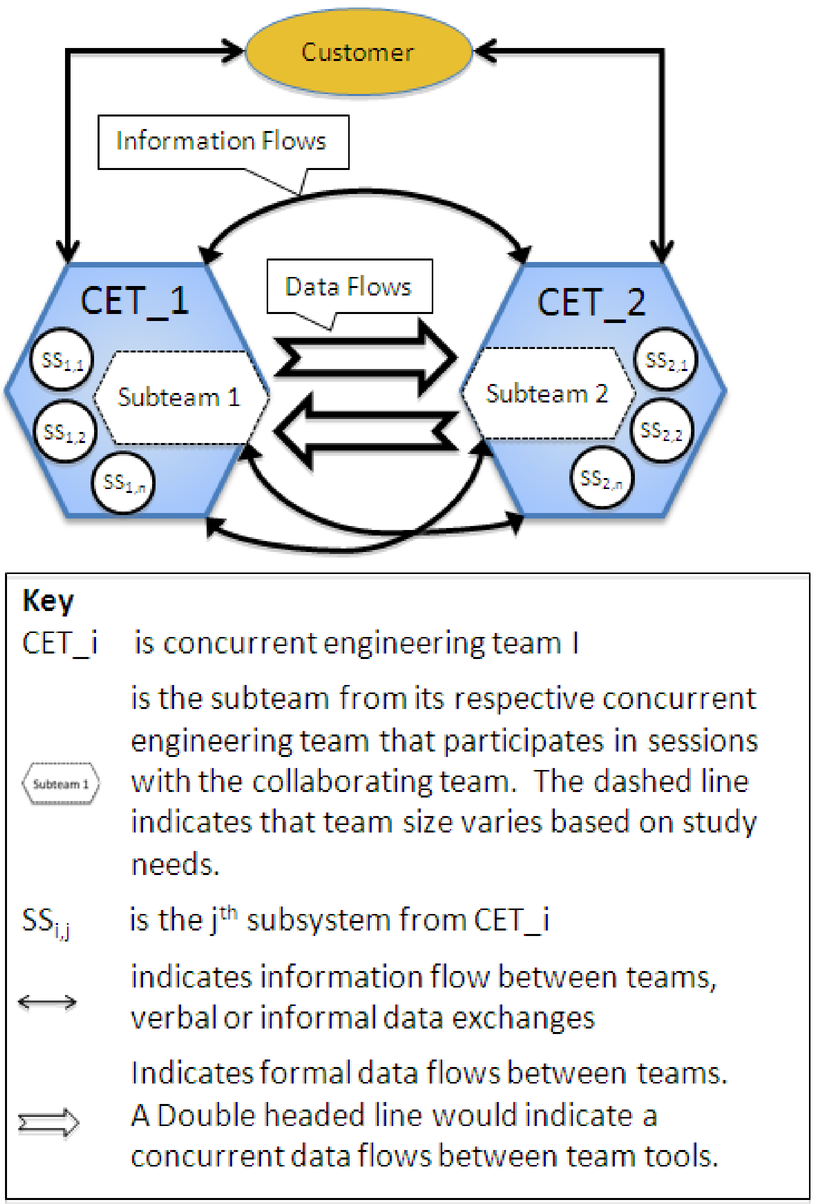

Figure 3: An Example Distributed Collaborative Team

In the distributed collaborative setting suggested here, the two collaborative teams would interact at the interfaces, through a limited number of information and data links. However, there are challenges to exchanging information in real-time between the two concurrent teams effectively. Hence, the proposed operational method would be to have the design task modularized in an efficient manner such that the teams can design serially rather than concurrently. For example, in a mission with multiple spacecraft, such as landers, orbiters and sample return elements could be partitioned such that one team designed the lander, and then passed the lander design to the other team, who would then design the orbiter. The design information from team 2 can be fed back to the first team in order to make adjustments to previously designed elements based on new design knowledge. In order to help situational awareness and teaming, a small subset of the each team participates in the design sessions of the other to facilitate information sharing. A distributed collaborative team requires more supporting infrastructure than a single team in order to facilitate the integration of the remote team, through data, audio/video, and information links.

Flexibility: The teams that are collaborating may be at different CET levels, and at different organizations with different management, different processes and tools. To enable collaboration between two or more teams, the interfaces between them need to be rigorously defined. In addition, the design study goals must be well defined and the objectives allocated between the teams ahead of the study. In order to be able to pass data parameters between teams, the parameter definitions and units must be agreed upon in advance and adhered to during the study. Given the level of definition and standardization needed to simply make collaboration between two different teams work, the resulting distributed team is not very flexible in responding to changes during the design session at all. Flexibility for a distributed collaborative team is typically low.

Teaming: The level of teaming within the individual teams may be high, but the overall teaming within the distributed team will be fairly low because the interactions between the teams are limited by geographical distribution and interaction only at the interfaces. Developing a shared identity – a key contributor to the efficiency of single, collocated concurrent engineering teams – is difficult in a distributed team setting. Some contributing factors may be unwillingness to spontaneously question assumptions made within the other team, or delays as team members try to verify each others' work due to lack of trust. This may lead to conflict that is difficult to resolve. This was observed in a case study by Hinds and Mortensen:

> Distributed teams reported more task and interpersonal conflict - shared identity moderated the effect of distribution on interpersonal conflict and shared context the effect of distribution on task conflict….team members struggle with different perspectives, unshared information and tensions between distant subgroups.[7]

However, analogous to the evolution of single CETs, it is possible that with repeated collaborations between teams may increase their familiarity with each others people and processes, thus increasing the team cohesion. Distributed collaborative engineering teams in aerospace have been sporadic one-time instantiations, so the potential benefits of repeated collaboration have not yet been demonstrated.

Situational Awareness: In distributed collaborative teams, the situational awareness is somewhere on the range between high and low. The challenges of collaboration between two teams, and the limitations of information exchange lower situational awareness, so it is necessary to sync design information at regular intervals. In the example of a distributed collaborative team described earlier, this syncing of information would happen when the design is handed over between the teams and would be supported by the subteams of participants that are shared between the two teams. Partitioning the design activities between the teams such that fewer parameters have to be shared would help reduce the need to maintain strong situational awareness.

Level 4b: Distributed Concurrent Team

In time, a distributed collaborative team may evolve into a distributed concurrent team, in which two or more teams collaborate with real-time parameter passing. However, the challenges of maintaining situational awareness and teaming across distributed teams in real-time is extremely challenging. To enable real-time interaction, there will need to be many information and data links between the teams, and there will be a need to periodically re-sync the teams to maintain situational awareness. In case of real-time collaboration, there are a number of issues to be dealt with, that are avoided in the collaborative, design-hand-off paradigm – the processes and tools of the different teams will need to be synchronized in order to work in parallel, participants will need to make a conscious effort to share information beyond the limited set of shared parameters in order to build a shared context, time-zone differences will need to be accommodated, differences in organizational practices of the different teams will need to be addressed, among other issues. The interfaces developed between the teams will need to be very well defined prior to the collaboration.

Flexibility: As described above, the interfaces between the teams in a distributed concurrent setting are very defined, and the design objectives must be distributed between the teams prior to the study. This is not conducive to accommodating changes in assumptions or study product needs. As such, the flexibility of distributed concurrent teams is low.

Teaming: Teaming in a distributed collaborative team is likely to be low. Within the teams, it can be high, but across the teams it is a challenge to develop a shared identity, though enabling multiple channels of communication between the teams may help. Initiating sidebars, which is integral to the concurrent design process to resolve issues, is difficult across teams when communication bandwidth is limited, and trust is difficult to establish due to geographical distribution. Abrams describes two types of sidebars – 'delegated', which are suggested directly by the study facilitator, and 'spontaneous', which are initiated by team members when they discover an issue to be clarified[8]. Abrams also describes a case study with two concurrent engineering teams in distributed team, in which he observed very few spontaneous sidebars, simply because of the overhead involved in formally setting up a sidebar between teams through an IT interface[8]. This describes a loss of one of the key benefits of concurrent engineering – spontaneous conversations to resolve issues. Hammond concludes that the reduction in communication leads team members to employ mental methods to compensate – such as employing heuristics, and introducing biases - which are detrimental to the design process[6].

Situational Awareness: Maintaining situational awareness is a challenge in distributed teams, and without sufficient shared knowledge it is impossible to create a shared context. While more links between the teams helps increase SA, it also imposes a burden on the team members who now have to support links within their own teams and across teams simultaneously which may lead to decreased performance in their own design tasks. Situational awareness is likely to be low between teams, but can improve with a conscious effort to sync design assumptions often at defined times during the process.

From the above discussions, we conclude that be very difficult for a distributed team to be as efficient as a high performing single concurrent engineering team. It will be difficult to achieve low latency comparable to a single team, for example, and it will be very difficult to pass every parameter between teams to maintain design fidelity, unless the teams involved are clones. However, the benefits of leveraging more than one concurrent engineering team may outweigh the loss of efficiency in some cases. Involving multiple teams will allow collaborating organizations to get buy in for decisions, as both teams will be involved in the system decision making. Multiple teams can also be very valuable in cases where one or the other organization has a particular expertise in a type of spacecraft design. But it is not always a more-is-better solution – it is important to carefully consider the costs versus the benefits of creating a distributed collaborative or distributed concurrent team, and to understand their limitations.

V. Summary

While concurrent engineering concepts have brought about extensive savings in the time and cost of concept development in aerospace, these teams should be judiciously applied. The most effective use of concurrent teams requires a better understanding of the strengths and weaknesses of different types of teams. The identification of the CET Attributes and the overall CET taxonomy described in this paper provides a method for designing the processes, products, infrastructure, and tools so that a concurrent engineering team meets an organization's needs.

For example, even the simple table shown below (see Table 1), which briefly summarizes how the CET attributes vary across the different levels of design teams can be used to gain insight into the limitations of the different types of teams. These attribute values are for typical teams in each Level, but clearly, teams can deviate from the values listed here. For example, a traditional team may have high Teaming in some circumstances, but there are more obstacles to overcome in order to achieve it. The implications are that Traditional Teams produce high fidelity designs but at higher cost, lower latency and may lack flexibility to sudden design changes. This is why they are best used later in the lifecycle when the mission requirements are more stable. Collaborative teams are flexible but tend to provide lower fidelity. Concurrent teams tend to be inflexible to process and tool changes while flexible to rapid parameter assumptions yet still maintaining their established design fidelity. It also implies that fully distributed CETs should not be pursued unless the payoff is high as there are many obstacles to overcome.

	Flexibility		Teaming	Situational Awareness
	Flexibility of methods and processes	Flexibility to changes in design assumptions/parameters		
Traditional Team	high	low-med	low-med	low
Collaborative Team	high	med	high	med
Concurrent Team	low	high	high	high
Distributed Teams	low	low	low-med	low-med

Table 1: Describing types of aerospace concurrent engineering teams using CET Attributes

VI. Next Steps

In future work we will use the framework described here to better understand how to improve the ability of CET to work more in a more distributed setting. Distributed collaborations involve diverse and geographically distributed concurrent engineering teams, and this framework will enable the identification of the strengths and weaknesses of these collaborations by allowing us to infer the characteristics and performance of distributed teams based on the single teams involved. While it is tempting to approach the distributed collaboration issue with a technological battle-axe, there is a need to first understand the sociotechnical implications of distributed collaboration among multiple team levels. This framework will also provide a basis for identifying the scenarios in which each type of concurrent team can be most effectively used, and provide guidance for how new concurrent engineering teams with the desired attributes can be developed. There is also work being done in the management field related to geographically distributed team collaboration that may inform the development of distributed CET, and an analogy can be drawn to frameworks for designing large collaborative engineering systems, such as Systems-of-Systems. These parallels need to be studied in depth in order to further develop this framework and extend it to the design of distributed concurrent engineering team collaborations.

Appendix

See Ref. 4 for a detailed discussion of Concept Maturity Levels.
A summary table from Ref. 4 is excerpted below.

Concept maturity levels are defined as follows:

- CML 1 - "Cocktail Napkin": Objectives and basic approach.
- CML 2 - Initial Feasibility: High-level physics, mass and cost assessments. Validate that mission (or instrument) concept is viable.
- CML 3 - Trade Space: Expansion of objectives and architecture trade space with elaboration and evaluation of performance cost and risks.
- CML 4 - Point Design within Trade Space: Subsystem-level design & cost estimates.
- CML 5 - Concept Baseline: Relationships and dependencies, partnering, heritage, technologies, key risks, mitigation plans and system make-buy approaches.
- CML 6 - Initial Design: Requirements and schedules to subsystem level, grassroots cost agreements, schedule, and V&V approach for key areas.
- CML 7 - PMSR/MDR; Preliminary Cost-Schedule-Design Integrated Baseline: Prelim Project Plan.
- CML 8 - PDR; Final Cost-Schedule-Design Integrated Baseline: Baseline Project Plan.

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