Concurrent Engineering Approach to Reducing Design Delivery Time

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Abstract: A common method used to reduce project delivery time is to overlap sequential activities. Evolution and sensitivity characterizations of design activities provide a practical tool for identifying overlapping opportunities. The faster the evolution of information in an activity, the less risky it is to begin a downstream activity before the upstream activity is finalized. Also, the lower the sensitivity to changes in upstream information, the less risky it is to overlap activities. A methodology for determining the evolution and sensitivity of design activities has been developed through a series of expert interviews. The evolution of an activity can be determined by evaluating the levels of design optimization, constraint satisfaction, external information exchange, and standardization. The sensitivity of an activity can be determined by evaluating activity constraints, input variables, and the level of design integration. This framework for characterizing design activities in terms of evolution and sensitivity will lead to significant reductions in project delivery times.

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Introduction

One way to reduce overall project delivery time (from design through construction) is to reduce design delivery time through the overlapping of sequential activities. A key to overlapping activities is management of the information transfer between activities. The manufacturing industry has recognized this fact and has developed concurrent engineering principles that integrate the knowledge generated in the design and manufacturing processes. This has lead to 20–50% reductions in product development times (Blackburn 1991).

Just as the manufacturing industry responded to the pressures of reducing product development time, so too must the architecture, engineering, and construction (AEC) industry respond by reducing project delivery times. To some extent, the industry has recognized this need and categorized and identified schedule reduction techniques. Schedule reduction tools, such as single design-build contracting, using preferred suppliers, and locating design staff at the construction site, have all been used successfully on a project-by-project basis to reduce overall delivery times (Songer et al. 2000). The term "flash-tracking" has even been used in the industry to indicate a project performed on a very short schedule.

Designers are under pressure to reduce design times to allow construction to proceed sooner, thus reducing overall project delivery time. Currently there is no formalized process for design managers to meet this challenge and most resort to employing ad hoc methods for reducing design delivery times. One way to achieve sustainable reductions in design delivery time is to develop a framework based on concurrent engineering principles, which can be used to evaluate and relax information dependencies in the design process. As illustrated in Fig. 1, removing information dependencies allows sequential activities to be overlapped to reduce the project schedule.

Background

Concurrent engineering (CE) is a production management philosophy that has received much attention in manufacturing, and to a lesser extent construction, over the past several decades. In order to achieve desired time-saving goals, concurrent engineering advocates concurrent, overlapped processes instead of sequential product and process design (Prasad 1996). Similarities between product development in manufacturing and the design-construction process in the AEC industry have led several researchers to address concurrent engineering in the AEC industry (de la Garza et al. 1994; Eldin 1997; Pena-Mora and Li 2001).

The extent to which two activities can be effectively overlapped depends on the relationship between those activities (Prasad 1996; Yassine et al. 1999). Prasad (1996) describes four types of relationships that are possible between activities: (1) dependent activities, (2) semi-independent activities, (3) independent activities, and (4) interdependent activities (Fig. 2). For dependent activities, one activity requires information from a second activity before the first activity can be started. Semi-

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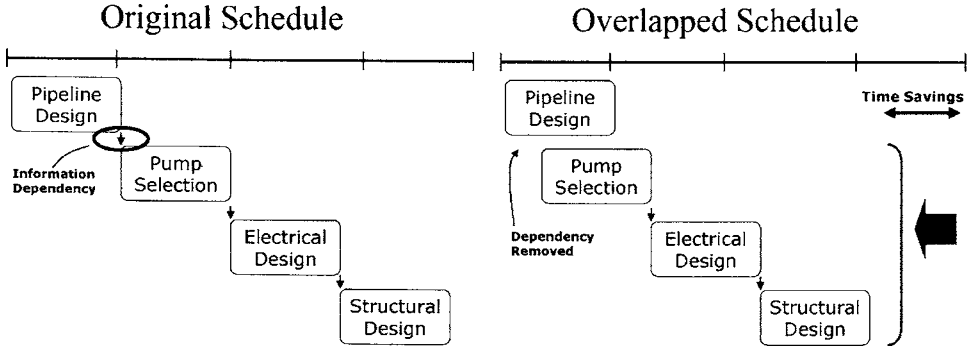

Fig. 1. Concept of concurrent execution of design activities

independent activities are characterized by one activity requiring only partial information from other activities before it can begin. Independent activities require no information from one activity before the other activity can begin. Interdependent activities require a two-way information exchange between the activities before either can be completed.

Among the four possible activity relationships, only independent activities can be overlapped without any risk of delay or rework. Dependent activities carry a risk when they are overlapped. When two activities are dependent, the downstream activity relies on information from the upstream activity. When dependent activities are overlapped, the downstream activity must begin before all the information is available from the upstream activity. Overlapping dependent activities increases the risk of delay or rework that results from changes in the upstream activity that affect assumptions made when starting the downstream activity. Increased communication and exchange of preliminary information becomes very important when overlapping dependent activities.

The degree to which dependent design activities may be overlapped is defined by the nature of the information exchange between the activities. Concurrent engineering literature (Krishnan et al. 1997; Loch and Terwiesch 1998) describes this information exchange between an upstream task and a downstream task in terms of the natural rate of information evolution in each task and the sensitivity of the downstream task to changes in upstream information (Fig. 3).

In simple terms, the development of information and knowledge in a design task can evolve quickly or slowly (Fig. 4). An example of the concept of design task evolution is the selection of a pump for a pump station. Initially, several pump types, with a range of manufacturers and models, may be under consideration by the engineer. The time it takes to narrow the pump selection and determine the final pump type, make, and model may not occur until the very end of the task. In a sequential operation, the structural engineer waits until the final pump is selected and then uses the final pump dimensions and weight to design the pad for the pump. When tasks are overlapped, however, the structural engineer may design the pad based on a range of possible pumps. As the final pump selection evolves, the information provided to the structural engineer may change, which could require additional work on the part of the structural engineer. The amount of additional work required is a measure of the sensitivity of the downstream task to changes in upstream information.

The evolution and sensitivity characteristics of a task suggest appropriate strategies for achieving overlap. According to the seminal work by Krishnan et al. (1995, 1997) overlapping should take one of four forms depending upon the nature of information evolution and sensitivity. The best situation for overlapping occurs when evolution is fast and sensitivity is low. In this situation both exchange of preliminary design information and early finalization of the upstream design information is recommended (referred to as distributive overlapping). If there is slow evolution and low sensitivity then overlapping through the exchange of preliminary design information is recommended (referred to as iterative overlapping). Highly sensitive activities with fast evolution are best overlapped by early finalization of upstream information (referred to as preemptive overlapping). Highly sensitive activi-

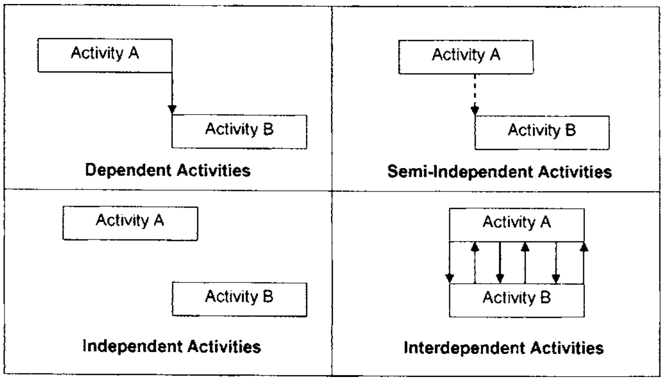

Fig. 2. Four types of activity relationships (adopted from Prasad 1996)

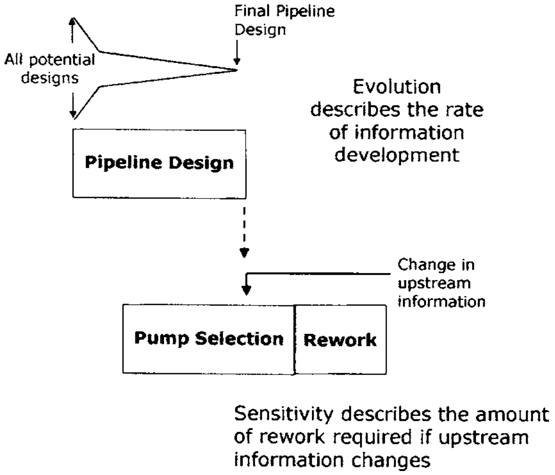

Fig. 3. Illustration of evolution and sensitivity definitions

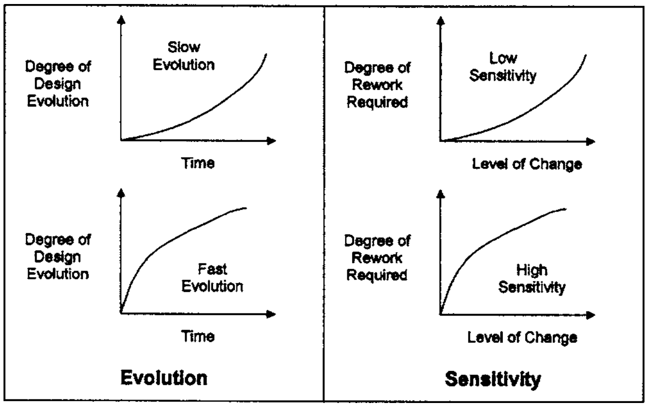

Fig. 4. Conceptual ranges of evolution and sensitivity

ties with slow evolution are the least likely to benefit from overlapping and should be decomposed to subactivities, if possible (referred to as divisive overlapping).

A key to using evolution and sensitivity characteristics to identify overlapping opportunities is to be able to quickly and accurately characterize design activities. This paper presents a classification system for evolution and sensitivity in design activities based on the results of exploratory interviews with design professionals.

Methodology

This paper addresses the issues of how to characterize design activities in terms of evolution and sensitivity. The specific research questions addressed in this paper are (1) How can design activities be characterized in terms of information evolution? and (2) How can design activities be characterized in terms of downstream sensitivity? As recommended in the seminal work by Krishnan et al. (1997), this study used design professionals to develop evolution and sensitivity characterizations for design activities. The study design grouped the design professionals into sector-based case studies depending on the type of design work they performed. Case study protocols, as suggested by Yin (1994), were used to design and validate the research.

Exploratory interviews with each design professional were performed to collect activity characterization information. The case studies covered three sectors in the AEC industry—roadway design, water/wastewater treatment plant design, and mechanical and electrical design for building systems. The results of the exploratory interviews were used to develop a process for characterizing design activities in terms of evolution and sensitivity.

Sixteen exploratory interviews were conducted as part of the sector-based case studies. The interview format was semistructured, exploratory interviews. That meant that there were no fixed questions, but rather the interviewer had a general list of topics that were used to guide the interview (Oppenheim 1992). The initial list of topics was derived from the research questions and the background literature review. The list of topics was refined and added to throughout the course of the interviews. There was no maximum to the number of interviews that could be conducted; however, there came a time when no new information was being generated through the interviews. This was considered to be the saturation point. At this point, no further interviews were deemed necessary (Oppenheim 1992).

The exploratory interviews resulted in large amounts of qualitative data that required analysis. The affinity diagram method was used to organize and generate an understanding of the information (White et al. 2002). The following sections of this paper present the resulting framework and validation approach for characterizing design activities in terms of evolution and sensitivity.

Information Evolution

Evolution describes the rate at which design information is generated from the start of an activity through the completion of the activity. In a quantitative approach, the evolution function would take the form of a relationship between time from the start of the activity and the degree of evolution (how close the design is to the final value) or percent of information finalized. This relationship is illustrated in Fig. 4. As Krishnan et al. (1997) acknowledge, it may be difficult to obtain this detailed information in practice. Therefore they suggested a primary classification framework that considered the extreme values of evolution (fast and slow). This still provides insight into overlapping opportunities for dependent activities. This qualitative framework was carried forward in this research.

The exploratory interviews with design professionals provided valuable insight into identifying those activity characteristics that cause an activity to have either fast or slow evolution. During the exploratory interviews, the design professionals were questioned as to the process for completing common design activities in their area of expertise. Once those activities were identified, they were then questioned as to whether they would consider an activity to be fast or slow evolving and what was it about that activity that determined its rate of design evolution.

As a result of the exploratory interviews, four key determinants of evolution were identified:

1. Design optimization: the level of optimization performed on design elements or the number of design alternatives evaluated;
2. Constraint satisfaction: the flexibility of design elements in satisfying constraints (such as physical limitations);
3. External information exchange: the amount of information received from or reviewed by external sources (such as client reviews or vendor data); and
4. Standardization: the level of standardization in the design product and/or the design process.

Design optimization refers to the level of optimization performed on design elements or the number of design alternatives evaluated. An example of design optimization is the balancing of cut and fill quantities for the earthwork on a roadway project. To minimize the amount of soil that must be hauled away, the designer attempts to balance out the volume of cut areas with the volume of fill areas. This is an iterative process that requires adjusting the roadway design until a reasonable balance is achieved. An activity that includes the evaluation of many alternatives or optimization of a parameter will have a slower evolution than an activity without these characteristics.

Constraint satisfaction describes the flexibility of the design in meeting physical limitations. An example of a design activity that must satisfy constraints is the addition of a new pipe to an existing pipe gallery. The designer of the new pipe must route the pipe in such a way that it avoids the existing pipes and walls and allows for maintenance access, while providing adequate flow for the material it is conveying. The existence of physical constraints results in a loss of flexibility, and thus may require multiple iterations to meet the constraints and result in a slow evolution characterization. Conversely, constraints can also limit the number of options to such an extent that no optimization is required, because only one solution will suffice.

External information exchange refers to the amount of information that is received from or reviewed by external sources. A common form of external information exchange is the review process conducted by clients and regulatory agencies. Activities that require information from outside sources (including equipment vendors, clients, or designers of other activities) that result in multiple iterations of design will have a slower evolution than those that do not require external information exchanges. As a point of clarification, the determinant of external information exchange does not include the information passed from an upstream activity to a downstream activity in a simple sequential project execution. However, if an activity requires information from multiple external sources, which could lead to design iteration, then this information will affect the evolution of an activity.

Standardization describes the extent to which design calculations or the design process is standardized. Standardization of a process or piece of equipment will tend to move an activity toward a faster evolution. Most of the standardization that arose in the exploratory interviews included standardized calculations and the use of standard ("off the shelf") equipment. One roadway project discussed in interviews used a standardized bridge design to decrease evolution and speed up the design process. These factors tended to limit the extent to which designs are optimized, and thus provided a faster evolution.

Based on the interview responses, the nexus between the four determinants of evolution is activity iteration. To some extent each of the four determinants of evolution relies on activity iteration as a determining factor. That is, design information in those activities with iteration evolves more slowly than in activities without iteration. Another observation from the interview results is that in the absence of time pressures, most designers would prefer to include iterations in their designs to find the optimal solution for a particular activity. This indicates that there is a natural tendency toward a slow evolution in many design activities.

The natural evolution characteristics of an activity describe the rate at which information is generated in the absence of any outside constraints or pressures. In an ideal situation where time and resources are not constrained, allowing an activity to progress at its natural evolution should produce the best design for that activity. This is typical of a traditional sequential design process where work is ordered such that all information needed for a particular activity is available at the start of that activity. There are not many ideal situations, however, which means that most design is performed under time and/or resource constraints. These time and resource constraints can lead one to adopt actions that change the natural evolution of an activity (generally taking a slow evolving activity and moving it toward a fast evolving activity).

In the case of time constraints, actions that speed up the design process are desirable. These actions can be aimed at reducing the time it takes to complete an individual activity (compression) or they can be aimed at reducing the overall design schedule through concurrent engineering (overlapping of sequential activities). In both of these approaches, changing the evolution of an activity from its natural state to a faster state can result in time savings.

A faster evolution does not have to mean a shorter duration for an activity (see Fig. 5). Evolution is defined in terms of the rate at which information is generated, which does not necessarily relate to the overall duration of an activity. A slow and a fast evolving activity may both take 5 days to complete with the only difference being the rate at which information is produced. Changing the evolution characteristics of an activity from slow to fast may mean that a particular batch of information that was originally produced near the end of the activity (say Day 5) is now available near the beginning. Some of the remaining information may still take until Day 5 to produce, which means that the overall activity duration has not changed, just the evolution.

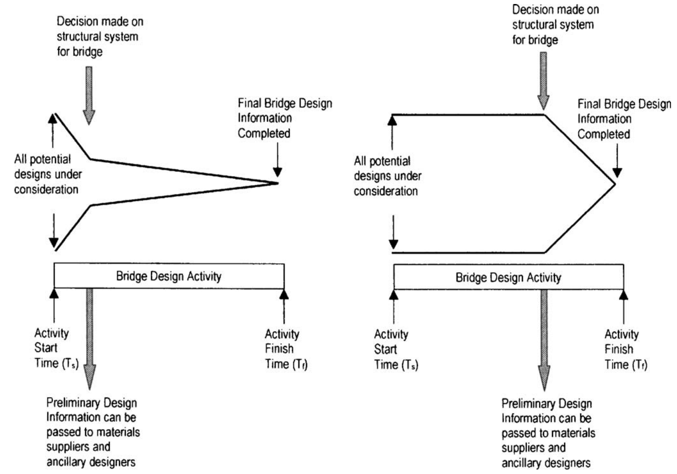

Fig. 5. Fast (left) versus slow (right) evolution

Evolution characterizations do not provide information on when each piece of information is produced in an activity, but rather provide a bigger picture of the general rate of information evolution. If there is a large batch of information produced in an activity, this can greatly influence the rate of evolution. In that case there may be a need to identify that batch of information, especially if it is a precursor to other downstream activities.

Evolution characterizations can be used in project scheduling decisions to identify potential overlapping opportunities. In general, activities with fast evolution are more amenable to overlapping than activities with slow evolution. However, when making the decision to overlap activities, one must consider that there is a risk that a particular piece of information may not be finalized before the downstream activity begins. In this situation, strategies, such as using preliminary information, can be adopted to allow the downstream activity to proceed.

The use of preliminary information (as well as other overlapping strategies) introduces the risk that the preliminary information may change before it is finalized. The amount of rework that must be performed, if preliminary information changes, is a factor of the sensitivity of the downstream activity to changes in the upstream information.

Information Sensitivity

A second goal of the exploratory interviews was to solicit input on characterizing activities in terms of their sensitivity to changes in upstream information. Sensitivity becomes important when one activity is dependent on another activity. This dependency between the two activities can take many forms. Among design activities the most common dependencies are information and resources. This paper focuses on information dependencies and the sensitivity of these dependencies to changes in upstream information. Therefore this paper assumes that there are enough resources available to eliminate resource dependencies between activities.

Dependencies drive the order in which activities are sequenced. Activities in most projects are performed in a sequence that is determined by the relationships between activities. Activities that depend on information from another activity are ordered so that all required information is available when the activity begins. Overlapping dependent activities, that is, starting a downstream activity before all upstream information is finalized, involves a certain amount of risk. This risk depends on the assumptions made to begin the downstream activity and the sensitivity of the downstream activity to changes in the assumptions when all upstream information is finalized.

Sensitivity in this research refers to how much rework (measured in additional time) is required on the downstream activity if upstream information changes. This relationship is illustrated in Fig. 4 where the horizontal axis refers to the extent that upstream information is changed. Therefore a highly sensitive activity would require a large amount of rework if a piece of input information changed just a small amount. An activity with low sensitivity can sustain large changes in input information with only minimal rework. This definition of sensitivity is consistent with the definition developed by Krishnan et al. (1997).

Three key determinants of sensitivity were gathered from the exploratory interviews with design professionals:

1. Constraint sensitive: the proximity of downstream design to a boundary or constraint;
2. Input sensitive: the level of dependence of downstream design on specific inputs from other activities; and
3. Integration sensitive: the ability of downstream design elements to be separated from the entire system.

Constraint sensitivity refers to the proximity of downstream design to a boundary or a constraint. When downstream design elements are near a constraint, then changes in upstream information could result in significant work in the downstream activity. For example, when a selected pump is near the boundary of its design capacity, a change in flow rate or head loss could make the selected pump no longer acceptable. In this situation, the design process for pump selection would have to begin anew. This is an example of a highly sensitive situation. Another example of a constraint-sensitive situation is the design of piping runs that are located in a pipe gallery. The design of the piping runs is constrained by the dimensions of the pipe gallery. A change in the pipe gallery dimensions could result in significant rework if the pipes are located near the gallery walls.

Input sensitivity refers to the level of dependence of the downstream design on specific inputs from other activities. An example of an input sensitive situation is the design of an electrical system based on a particular piece of equipment. If that piece of equipment is changed, the design of the electrical system must start over.

Integration sensitivity refers to the ability of downstream design elements to be separated from the entire system. An example of an activity that is integration sensitive is designing the vertical alignment for a roadway. A change in elevation at one point along the alignment can "ripple" through the entire alignment, since it is difficult to isolate segments of the roadway design.

Unlike evolution, there are no natural, or inherent, characteristics of activities that determine their sensitivity to upstream changes in information. Rather, the results of the exploratory interviews indicated that sensitivity was affected by the design situation. Design managers must be familiar with the specific project circumstances to be able to identify the sensitivity of activities. This type of "situational sensitivity" is also mentioned by Krishnan (1996) when he states that sensitivity is "dependent on internal factors such as the communication among engineers, anticipation of the downstream engineers, and the flexibility of the development methodologies used." Interviewees in this study often cited the issue of design flexibility when discussing sensitivity characteristics.

Identifying the sensitivity of downstream activities is important in overlapping decisions. Starting a highly sensitive activity before all upstream information is complete entails an increased risk that significant rework will be required, thus eliminating some of the time savings due to the original overlapping. On the other hand, activities with a low sensitivity can be overlapped with little risk of rework required. By understanding activity sensitivities, project managers can make informed decisions on overlapping strategies.

Validation of Evolution and Sensitivity Determinants

Validation of the findings on evolution and sensitivity characterizations was performed using the validity tests described by Yin (1994). The four tests of validity include construct validity, internal validity, external validity, and reliability.

Construct Validity

Construct validity establishes the correct operational measures for the concepts being studied. This entails selecting the specific changes to be studied and then demonstrating that the selected measures of these changes reflect the specified change. For this research the concepts being studied were the activity characteristics that determine evolution and sensitivity. The definition of evolution and sensitivity used in this study was from the seminal work by Krishnan et al. (1997). To establish construct validity one must show that the identified activity characteristics (i.e., the determinants of evolution and sensitivity) result from a common understanding of the terms "evolution" and "sensitivity." The approach for establishing validity of the construct was the use of multiple sources of data, through interviews with multiple designers within each sector-based case study. Similar responses from multiple interviewees demonstrated that there was a common understanding of the concept being studied. An example of a common interview response was the relationship between standardization and evolution. Several interviewees described the use of standard equipment in the design process as a way to speed up the evolution of an activity. This showed a common understanding of the concept of evolution among these interviewees.

Internal Validity

Internal validity establishes the accuracy with which information is captured and interpreted (Ritchie and Lewis 2003). This type of validation applies to the explanatory portion of case studies, where a causal relationship is being established (Yin 1994). This study employed affinity diagramming to organize the data and search for patterns. An affinity diagram is a technique for "organizing vast amounts of qualitative data to identify any natural patterns or groupings to allow a better understanding of a problem" (White et al. 2002). The determinants of evolution and sensitivity were developed through affinity diagraming by grouping similar interview responses and then creating a group name that was representative of the responses in that group.

The second approach used for establishing internal validity was reviewing the research results with a subset of the same designers as well as a small group of outside designers. Six validation interviews were performed (three from the original group of interviewees and three outside designers) to confirm the determinants of evolution and sensitivity. With a few exceptions, the interviewees were able to easily visualize how each of the determinants affected evolution or sensitivity, and in some cases, were able to provide examples from their work experiences. The hardest determinants for the interviewees to visualize were input sensitivity, integration sensitivity, and constraint satisfaction for evolution. Some interviewees required further definition and examples to accept these results.

External Validity

External validity establishes the extent to which a study's findings can be generalized. There are different levels of generalization—representational generalization (the extent to which findings can be generalized to the parent population), inferential generalization (generalizing from the context of the research study to other settings or contexts), and theoretical generalization (drawing theoretical propositions for general application) (Ritchie and Lewis 2003). This study used triangulation of data sources to promote representational generalization. Triangulation is the use of multiple sources of information to help confirm and improve the clarity of research findings (Ritchie and Lewis 2003). This study included data from three design sectors of the AEC industry to promote generalizations within each sector and also to the entire AEC design industry. Commonalities in the responses across each sector supported the belief that the results could be generalized to other design sectors in the larger AEC industry.

Respondent validation was also used to demonstrate external validity. Respondent validation involves taking the research results back to the original interviewees or a similar group to see if those who provided the original information confirm the interpretation assigned by the researcher (Ritchie and Lewis 2003). In the validation interviews, interviewees were asked to characterize the evolution and sensitivity of a small example project (either a pump station design or roadway design project). The interview responses were compared with characterizations made by the writer. The validation interview responses showed concurrence among the evolution and sensitivity characterizations. There was not, however, complete consistency with all responses. This does not indicate that the process for determining evolution and sensitivity is not valid, but does indicate areas where additional clarification of definitions and expectations are necessary to increase consistency.

Reliability

Reliability demonstrates that the operations of a study, such as the data collection procedures, can be repeated with the same results. To satisfy the reliability test, a detailed study protocol was developed that provides an overview of the project, describes field procedures, and presents case study questions (Bogus 2004).

Practical Applications of Evolution and Sensitivity Characterizations

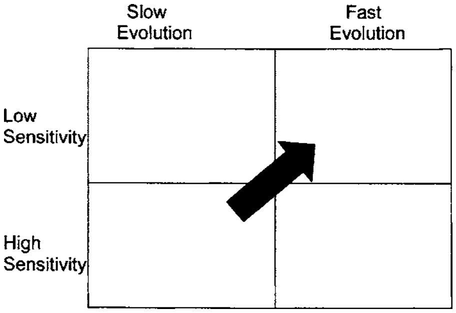

Fig. 6. Goal of potential overlapping strategies

Overlapping of sequential activities is a fundamental strategy in concurrent engineering for reducing project delivery time. However, overlapping strategies and methods for making overlapping decisions are not as well understood. The evolution and sensitivity characteristics of a task suggest appropriate strategies for achieving overlap. These characteristics, which describe pairs of activities in terms of upstream information evolution and downstream sensitivity to changes in upstream information, provide a hint of the information dependencies between the activities. By understanding these information dependencies, a project manager can use that information to identify appropriate strategies for reducing or removing those dependencies, and thus allow for activity overlap.

Potential overlapping strategies, in the context of this study, were those strategies that reduce or remove information dependencies between two activities. This study focused on information dependencies between activities that lead to the highly sequential nature of design schedules. By removing or reducing these information dependencies, the opportunity for overlapping activities increases, which can lead to significantly reduced delivery times.

The optimal situation for overlapping a pair of dependent activities is to have an upstream activity with a fast evolution and a downstream activity with a low sensitivity. This situation, however, exists rarely in the design process. The objective of overlapping strategies is to reduce or remove information dependencies by altering the existing activity characteristics to create a more favorable overlapping environment. There are two fundamental mechanisms by which the strategies described here reduce or remove information dependencies. First, some strategies act to speed up the evolution of upstream activities, thus making information available sooner to downstream activities. The second is to reduce the sensitivity of downstream activities to changes in upstream information (see Fig. 6).

As mentioned previously, the early release of preliminary information from an upstream activity to a downstream activity is one example of an overlapping strategy. Early release of preliminary information from the upstream activity speeds up evolution of that activity by allowing the downstream activity to proceed before the upstream design is complete. The early release of preliminary information has been discussed in research (Krishnan et al. 1997; Ballard 2000; Terwiesch et al. 2002) as well as used on design and construction projects.

Two examples of this strategy arose from the exploratory interviews. In the first case, the designer used preliminary information from the design of a structural steel system to place a fabrication order for that steel. The fabrication company was operating under a large backlog of orders, so there was a time lag between when the order was placed and when fabrication actually occurred. Therefore the designer was able to modify the fabrication order as the preliminary information became final, as long as fabrication had not started. By releasing the preliminary design information to procurement, the company was able to get their order in the fabrication queue earlier than if they waited until the final design was completed.

The second example involved the early release of design drawings prior to final review. For this large highway project, the designer and builder operated as a single design-build entity, which facilitated the release of preliminary design information for construction. By releasing preliminary information, construction was able to proceed sooner than if final design documents were used.

In both of these examples, time savings were achieved by allowing downstream activities to proceed based on preliminary information from the upstream activities. The risk of proceeding based on preliminary information is that this information may change as it is finalized and require significant rework in the downstream activity. The risk of change increases with an increase in the amount of activity overlap. In the fabrication example, any design changes that occur after fabrication has begun will add cost to the project if they result in the fabrication of unusable pieces. Similarly, the early release of design information for construction may also result in rework if the design changes significantly as it is finalized.

Using the characterization process presented in this paper, a project manager can quickly assess individual activity evolution and sensitivity. This information can then be used to make decisions on overlapping activities and strategies to reduce design delivery time. The characterization process also provides valuable input to existing models such as those developed by Krishnan et al. (1997); Roemer et al. (2000); and Pena-Mora and Li (2001). These models use evolution and sensitivity characterizations to provide a process for overlapping sequential activities to reduce project delivery time.

Together evolution and sensitivity characterizations and their relation to overlapping strategies illustrate a concurrent engineering approach to reducing design delivery time, and ultimately to reducing overall project delivery time. Ultimately, this fundamental understanding of evolution and sensitivity characteristics in design activities will lead to improved planning tools for fast-track design, as well as future research into the integration of design and construction activities.

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