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Strategies for overlapping dependent design activities

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Overlapping activities that are traditionally performed in a sequential manner can significantly reduce project delivery times. Overlapping, however, should be approached in a systematic manner to reduce the costs and risks. Information gathered from sector-based case studies and from the manufacturing domain suggest a formalised framework for identifying overlapping opportunities and strategies can be successfully implemented for infrastructure projects. This framework considers activity characteristics, such as evolution of upstream information and sensitivity of downstream activities to changes in upstream information, to identify appropriate overlapping strategies. Overlapping strategies, such as early freezing of design criteria, overdesign, and early release of preliminary information, are selected based on activity characteristics. These strategies operate either by speeding up the evolution of upstream information or by reducing the sensitivity of downstream activities. By aligning overlapping strategies with activity characteristics, project managers can make better decisions on when and how much to overlap sequential activities to reduce overall project delivery time.

Keywords: Concurrent engineering, project management, decision making

Introduction

The design and construction of large projects is a complex process. Rarely is the same design used for multiple projects, which results in a series of one-off designs. From a project management perspective, the design planning process involves bringing together numerous pieces of information from multiple designers to form the final design. Coordinating the flow of information in the design process is further complicated when the design schedule needs to be compressed.

A fundamental strategy for reducing project delivery times calls for overlapping dependent activities. The degree to which dependent design activities may be overlapped is defined by the nature of the information exchange between those 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 evolution of information development in each task and the sensitivity of the downstream task to changes in upstream information.

Overlapping dependent activities requires that work on the downstream activity starts before the required upstream information is finalised. Therefore, the downstream activity must begin with incomplete, non-optimal, or non-final information. The extent to which the information is likely to change is a function of the evolution of the upstream activity. The faster the evolution of the upstream activity, the less likely it is that upstream information will substantially change. The sensitivity of the downstream activity describes the extent to which changes in upstream information create rework in the downstream activity. Overlapping two dependent activities requires that either upstream information be passed downstream sooner (i.e. speed up evolution) or downstream activities reduce their sensitivity to changes in upstream information. The manner in which this process occurs is referred to as an overlapping strategy.

The primary objective of this research was to determine how to apply strategies to increase the overlap between dependent design activities. Inherent in this issue are several sub-questions such as: (1)

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Which strategies are available for overlapping sequential design activities? (2) Which of the identified strategies are appropriate based on evolution and sensitivity characteristics? and (3) What are the consequences of applying these strategies to overlap sequential design activities?

Overlapping of design tasks is not without risks or costs. Some of the risks and costs associated with overlapping, and more generally fast-track construction, include lack of design optimisation and coordination, increased levels of rework due to transfer of insufficient design information, increased materials wastage, inadequate coordination between design and construction, and inadequate scheduling of the work package interfaces (Fazio *et al.*, 1988; Williams, 1995). Because of the increased risk associated with overlapping of design, a formalised approach is necessary to reduce potential negative impacts.

In the seminal work by Krishnan *et al.* (1997), overlapping strategies were identified based on the evolution of information in the upstream activity and the sensitivity of the downstream activity to changes in upstream information. The best environment for overlapping occurs when the upstream activity is fast evolving and the downstream activity has low sensitivity. According to Krishnan *et al.*, evolution and sensitivity characteristics provide a framework for classifying the strength of the information dependencies between activities.

In the Krishnan *et al.* framework, if there is slow evolution and low sensitivity then overlapping through the exchange of preliminary design information is recommended (referred to as iterative overlapping). If evolution is fast and sensitivity is low, then both exchange of preliminary design information and early finalisation of the upstream design information are recommended (referred to as distributive overlapping). Highly sensitive activities with slow evolution are the least likely to benefit from overlapping and should be decomposed to sub-activities, if possible (referred to as divisive overlapping). Highly sensitive activities with fast evolution are best overlapped by early finalisation of upstream information (referred to as pre-emptive overlapping) (Krishnan *et al.*, 1995; Krishnan, 1996; Krishnan *et al.*, 1997).

By understanding the relationship between two dependent activities in terms of evolution and sensitivity, a project manager can use that information to identify appropriate strategies for overlapping the activities. This paper presents the results of a study that aligns multiple overlapping strategies to the evolution and sensitivity characteristics of design activities.

Methodology

As recommended by Krishnan *et al.* (1997), the initial work in this study used interview data from design professionals to develop the framework for characterising design activities in terms of evolution and sensitivity. The research methodology employed sector-based case studies to collect and organise activity characterisation information from exploratory interviews with design professionals. The case studies covered three sectors in the architecture, engineering and construction (AEC) industry—roadway design, water/wastewater treatment plant design, and mechanical and electrical design for building systems. Case study protocols were used to design and validate the research (Merriam, 1988; Yin, 1994; Stake, 1995).

A total of 16 exploratory interviews were conducted as part of the sector-based case studies. The interviewee group included design professionals from both public and private organisations, who were generally at a project manager level or above. Most interviewees had 10 years of experience or more. The interview format was semi-structured, which is appropriate for exploratory interviews. That means 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 is no maximum to the number of exploratory interviews that should 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 necessary (Oppenheim, 1992). Common ideas were observed among the interviews, so the number of interviews conducted was deemed sufficient.

Available overlapping strategies were determined from the exploratory interviews with design professionals and literature review. Strategies were selected for further study based on their ability to remove or reduce information dependencies that limit overlapping opportunities.

Definition of overlapping strategies

Potential overlapping strategies, in the context of design, are those strategies that reduce or remove information dependencies between two design 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.

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. Activity evolution in the design of civil infrastructure projects is determined by four factors (Bogus, 2004; Bogus *et al.*, 2005):

(1) *Design optimisation*: the level of optimisation 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).
(4) *Standardisation*: the level of standardisation in the design product and/or the design process.

Slow evolving activities are ones that optimise design parameters, evaluate multiple alternatives, have many constraints to satisfy or require external information exchange. Alternatively, fast evolving activities are standardised, without optimisation, alternative evaluation, constraint satisfaction or external information exchange. In general, the more iterations that are required in a design activity, the slower the evolution.

Activity sensitivity in the design of civil infrastructure projects is expressed in three ways (Bogus, 2004; Bogus *et al.*, 2005):

(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.
(3) *Integration sensitive*: the ability of downstream design elements to be separated from the entire system.

Sensitivity is defined by the amount of rework required in a downstream activity as a result of a change in upstream information. Downstream activities are more sensitive to changes in upstream information when the downstream design is near a constraint or boundary; when the downstream design depends on one key upstream input; or when the downstream design is integrated such that changes cannot be isolated.

The combination of an upstream activity with a fast evolution and a downstream activity with a low sensitivity results in the weakest dependency and creates a good overlapping opportunity. As the evolution of the upstream activity slows and the sensitivity of the downstream activity increases, the dependency between the two activities strengthens along with the risks of overlapping. Overlapping strategies can be applied to reduce the information dependency between activities to increase the amount of overlap and reduce the risks associated with overlapping. There are two fundamental mechanisms by which overlapping strategies can 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. Second, some strategies reduce the sensitivity of downstream activities to changes in upstream information.

Eight overlapping strategies were identified based on information gathered through the exploratory interviews with design professionals and concurrent engineering literature. These overlapping strategies are summarised in Figure 1 and described below.

Early freezing of design criteria

The early freezing of design criteria allows information from an upstream activity to be released to the downstream activity before the upstream design is complete. This strategy requires project participants to commit early in the design process to specific design criteria. The early freezing of design criteria reduces some of the uncertainty for designers of downstream activities; however, this reduction of uncertainty comes with a price. When design criteria are frozen early in a project, there is a likelihood that project costs may increase due to a lack of design optimisation. There is also a risk that the pre-established criteria may not be feasible in all situations. In this case, substantial rework may be required if downstream activities have already begun based on the initial design criteria. Eldin (1996) studied this strategy as a potential schedule reduction

Sensitivity	Evolution: Slow	Evolution: Fast
Low	Overdesign Early release of prelim info Prototyping No iteration/optimisation Standardisation Set-based design	Early freezing of design Overdesign Early release of prelim info Prototyping
High	Overdesign No iteration/optimisation Standardisation Set-based design Decomposition	Early freezing of design Overdesign

Figure 1 Basic overlapping strategy framework

technique and the exploratory interviews indicated that it has been used on highway projects to establish bridge design criteria.

Overdesign

Overdesign, or adoption of conservative assumptions, in the downstream activity allows work to begin before the upstream design is complete. By making conservative assumptions on the size or strength of project components, designers are able to proceed with the downstream activity before the upstream activity is completed, and in some cases, before the upstream activity has even begun. The risk of adopting an overdesign strategy is that the assumptions made concerning the upstream activity may not be conservative enough, thus requiring redesign or reconstruction of the downstream activity. When this occurs, all potential time savings are eliminated and cost additions are likely. As a result, there is a fine balance between increasing the conservativeness of your assumptions and maintaining a reasonable cost for the project. There is also a trade-off between the amount of overlapping and the certainty of upstream information. The more overlap there is between dependent activities (i.e. the closer the start of the downstream activity is to the start of the upstream activity), the more uncertain the upstream information is. This can affect the conservativeness of assumptions in an overdesign strategy and increase costs. This type of trade-off also applies to other strategies described here, such as the early release of preliminary information. Overdesign is mentioned in concurrent engineering research (Ballard, 2000) and the exploratory interviews indicated that it has been used on highway projects for the design of stormwater drainage pipes.

Early release of preliminary information

Early release of preliminary information from the upstream activity allows the downstream activity to proceed before the upstream design is complete. The risk of proceeding based on preliminary information is that this information may change as it is finalised and require significant rework in the downstream activity. The risk of change increases with an increase in the amount of activity overlap. Similarly, the early release of design information for construction may also result in rework if the design changes significantly as it is finalised. The early release of preliminary information has been discussed in research (Krishnan *et al.*, 1997; Ballard, 2000; Terwiesch *et al.*, 2002) and the exploratory interviews indicated that it has been used for steel fabrication orders.

Prototyping

Prototyping is the process of quickly compiling preliminary upstream design information into a working model of the ultimate system. It is understood that the working model is only a first-cut and not necessarily the final system. The initial prototype serves as a tool to promote communication among all project designers. Final definition of the system occurs through gradual revisions and enhancements to the original model (Boar, 1985). Prototyping allows the downstream activity to proceed as soon as the working model is finished, but before the upstream design is complete. Prototyping is similar to the early release of preliminary information, but applies to complex systems, where there are many pieces of information to relay to downstream activities. The risk, however, is that the original prototype will be based on poor criteria, and thus require substantial revisions, which could result in significant rework for downstream activities. Prototyping is often used in the manufacturing industry.

No iteration or optimisation

Limiting iteration or optimisation in a slow evolving activity speeds up the evolution of the activity and allows information to be passed on to downstream activities earlier in the process. This strategy applies to activities with a naturally slow evolution, where iteration or optimisation delays the availability of information to downstream activities. Under this strategy, limits would be placed on the number of iterations allowed before information must be passed on to downstream activities. Ballard (2000) discusses this strategy in terms of a deferred commitment, where iteration is put off until there is simply no more time to perform the iterations. A no iteration or optimisation strategy as presented here does not suggest waiting to perform the iteration, but rather, places a time constraint on the process, which has the same effect of limiting the amount of iteration that can occur. Similar to the early freezing of design criteria, there is a likelihood that project costs may increase due to a lack of design optimisation. Likewise, when applied to activities with a naturally slow evolution, this strategy will move those activities from a slow evolution model towards a fast evolution model.

Standardisation

Adopting standardised products, components or design speeds up the evolution of upstream activities and allows information to be passed on to the downstream activity earlier in the process. Standardisation refers to the adoption of design practices or components to be used repetitively on a project (Gibb, 2001). Similar to other strategies, the likelihood that project costs may increase due to a lack of design optimisation increases. However, in some cases standardisation may decrease project costs by eliminating sub-optimal designs and increasing constructability. Sub-optimal design refers to situations where one designer might optimise their part (e.g. a structural engineer who focuses on minimising the amount of rebar) at a cost to the entire project (such as more complex construction). When applied to activities with a naturally slow evolution, standardisation will move those activities from a slow evolution model towards a fast evolution model. The exploratory interviews indicated that standardisation has been used for bridge girder design.

Set-based design

Set-based design, or carrying forward multiple upstream designs, decreases the sensitivity of downstream activities to changes in upstream activities. In set-based design, a designer for one component develops sets of solutions (or designs) in parallel with designers of other components. Design progresses as the solution sets are gradually narrowed based on testing, customer input and manufacturability. As the set of possible solutions narrows, designers must agree to stay within this group of solutions. The final design represents a gradual convergence of the individual designs for all components into a final integrated solution. Set-based design saves time by allowing downstream activities to begin developing their set of feasible designs at the same time that upstream activities are developing their design sets. One consequence of set-based design, however, is the added cost of developing multiple designs for each activity or a more conservative single design. Set-based design is a strategy first used by Toyota to reduce product development time for new automobiles (Sobek *et al.*, 1999).

Decomposition

When applied to an upstream activity, decomposition of the activity into smaller packages may create faster evolving activities. When applied to a downstream activity, decomposition of the activity may create activities with lower sensitivity. Decomposition is a second-tier strategy to be employed in situations where other strategies are not effective. The objective of decomposition is to create new activities that can then be re-analysed and overlapped using one of the previously mentioned strategies. Decomposition of activities into smaller packages is a strategy that has been discussed in concurrent engineering literature (Krishnan *et al.*, 1997; Ballard, 2000).

Basic overlapping strategy framework

The work by Krishnan *et al.* (1997) provides a foundation for a basic overlapping strategy framework. The framework aligns overlapping strategies according to the final evolution and sensitivity designations (e.g. slow evolution/low sensitivity, fast evolution/low sensitivity). The appropriateness of applying an overlapping strategy to activities with certain evolution and sensitivity characteristics is derived from the manner in which the strategy removes or relaxes information dependencies. Aligning strategies to activity characteristics allows project managers to select the most appropriate overlapping strategy for a given situation.

Strategies that speed up evolution

The following strategies act to speed up the evolution of information so that downstream activities can begin earlier:

- *Early freezing of design criteria*: Freezing the upstream design essentially eliminates the likelihood of changes in upstream information after downstream activities have begun. The final design however, is greatly affected by the quality of information in the upstream activity at the time of freezing. Therefore, early freezing of design criteria is recommended only when the upstream activity is fast evolving.
- *Early release of preliminary information and prototyping*: When applied to an upstream activity, the release of preliminary information or a preliminary prototype essentially 'fools' the downstream activity into thinking that the upstream information is complete so that the downstream activity can begin. The preliminary information, however, is not finalised, and downstream activities that are begun with preliminary information run the risk of that information changing after the downstream activity has begun. Therefore, these two strategies are only recommended when the downstream activity has a low sensitivity to changes in the preliminary upstream information.
- *No iteration or optimisation and standardisation*: A strategy that eliminates or reduces iteration has the effect of taking a slow evolving activity and turning it into a fast evolving activity. Both of these strategies only apply to upstream activities with a slow evolution, since by definition, fast

evolving activities do not have iteration or are already standardised.

Strategies that reduce sensitivity

The following strategies act to reduce the sensitivity of downstream activities to changes in upstream information:

- *Overdesign*: The extent to which sensitivity is reduced depends on the quality of information used for overdesign in the downstream activity. Upstream activities with a fast evolution are, by their nature, able to provide better information to downstream activities for them to base their overdesign assumptions on. However, overdesign is also appropriate for upstream activities with a slow evolution, since more conservative assumptions can be made for overdesign. The consequences of overdesign based on information from a slow evolving upstream activity will be greater than that for a fast evolving upstream activity because of the level of design necessary.
- *Set-based design*: Under a set-based strategy, a downstream activity could begin by developing designs for two or more alternatives (sets) that may result from an upstream activity. A set-based strategy assumes that the upstream activity is evaluating multiple alternative designs; therefore, it is most applicable when the upstream activity is slow evolving.

Figure 1 summarises the basic overlapping strategy framework, which links overlapping strategies to evolution and sensitivity characterisations. As shown in Figure 1, there are more strategies that apply to slow evolving activities than to fast evolving activities. Considering that the natural evolution of most activities tends toward slow, this result is useful. In addition, slow evolving activities have the least potential for overlapping unless their natural evolution is modified to make more information available sooner in the process or unless downstream sensitivities are reduced.

As presented above, there are multiple strategies available for overlapping dependent activities. Choosing the most appropriate strategy depends on the evolution and sensitivity characteristics of design activities and also the specific project situation. The evolution and sensitivity characteristics of activities can be used to further narrow down potential overlapping strategies by looking at the determinants of evolution and sensitivity.

Enhanced overlapping strategy framework

An enhancement to the overlapping strategy framework is to align specific strategies with the specific determinants of evolution and sensitivity. This enhanced overlapping framework relies on a detailed analysis of the appropriateness of each strategy as it relates to the specific evolution or sensitivity characteristics of a given activity pair. A complete discussion of the nuances of selecting overlapping strategies based on the determinants of evolution and sensitivity are beyond the scope of this paper. Aligning strategies at the determinant level provides information about which strategies are most appropriate for a given context. For example, consider the set of strategies in the basic overlapping framework (Figure 1) that apply when the evolution is slow and the sensitivity is high (lower left corner). These strategies are overdesign, no iteration/optimisation, standardisation, set-based design and decomposition. Among these strategies, two (no iteration/optimisation and standardisation) act to speed up evolution and two (overdesign and set-based design) act to reduce sensitivity. Decomposition could affect either evolution, if applied to an upstream activity, or sensitivity, if applied to a downstream activity.

In creating the enhanced overlapping strategy framework, each strategy is considered in terms of how effective it would be given a specific determinant of evolution or sensitivity. The framework is then built on a determinant-by-determinant basis. Figure 2 illustrates this process for activity pairs with slow upstream evolution and high downstream sensitivity. In Figure 2, the determinants of evolution are listed along the top row and the determinants of sensitivity are listed in the left column. Consider, then, the upper left corner of the matrix, which corresponds to the evolution determinant 'high levels of optimisation or evaluation of many alternatives' and the sensitivity determinant 'high constraint sensitivity'. The strategies that act to speed up evolution are only affected by the determinants of evolution and are independent of the determinants of sensitivity. The opposite also applies—strategies that act to reduce sensitivity are only affected by the determinants of sensitivity.

The effectiveness of a strategy to speed up evolution depends on the activity characteristics that cause an activity to evolve information slowly. Activities that are slow evolving due to high levels of design optimisation (e.g. minimising the amount of concrete in a foundation) or due to high levels of external information exchange (e.g. between the client and the design team) may be overlapped by reducing the number of iterations allowed in the design process or the number of changes in information allowed (no iteration/

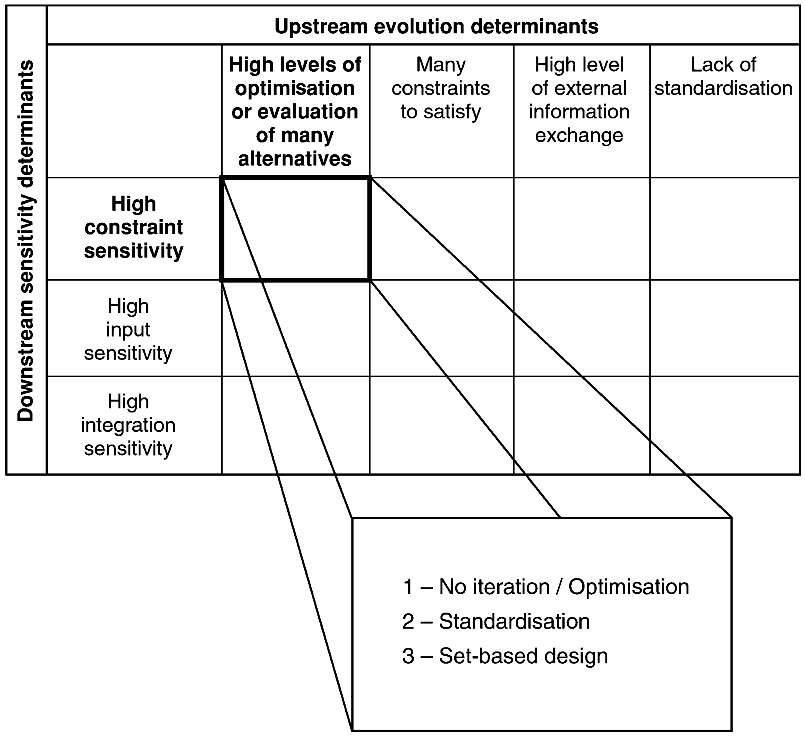

Figure 2 Example enhanced overlapping strategy framework for high levels of optimisation and high constraint sensitivity

optimisation strategy). These types of activities also benefit from standardisation. Therefore, these two strategies—no iteration/optimisation and standardisation—are placed in the column corresponding to 'high levels of optimisation or evaluation of many alternatives' as in Figures 2 and 3. Likewise, the overlapping strategies that act by reducing sensitivity in downstream activities to changes in upstream information are closely linked to the determinants of sensitivity in the downstream activity. For example, the overdesign strategy is most appropriate when a downstream activity is sensitive to input information from an upstream activity. By making conservative assumptions regarding the input information required, the downstream designer can reduce the sensitivity of the downstream design to the final input value. Conversely, overdesign is not appropriate when the downstream activity is constraint sensitive. In this situation, constraints must be met and overdesigning the downstream activity may exceed the given constraints. Set-based design is a better choice for situations where the downstream activity is constraint sensitive. Therefore, set-based design is placed in the row corresponding to 'high constraint sensitivity' and overdesign is placed in the row corresponding to 'high input sensitivity' in Figures 2 and 3.

Aligning strategies at the determinant level narrows down the choices of strategies for each overlapping situation. However, it also increases the amount of information that must be considered in the decision process, since decision makers now have to consider not only whether an activity is fast or slow evolving, but also, the key determinant of the evolution characteristic.

Practical application

The first step in utilising the basic overlapping framework is to develop a critical path network schedule for the design process assuming no activity overlap. Time savings are only achieved when activities on the critical path are overlapped. This non-overlapped, or presumptive, schedule also provides the baseline against which time savings can be measured for the overlapped schedule. Once the activities on the critical path have been identified, the second step is to determine the evolution and sensitivity characteristics of each activity along the critical path. The evolution and sensitivity characteristics can be assigned using the determinants of evolution and sensitivity.

Consider, for example, a pipeline design activity where alternative routes are being evaluated before selecting the final design route. This activity would be characterised as slow evolving due to the evaluation of multiple alternatives (referred to as 'design optimisation' under the determinants of evolution). The pipeline design activity feeds information on head loss and

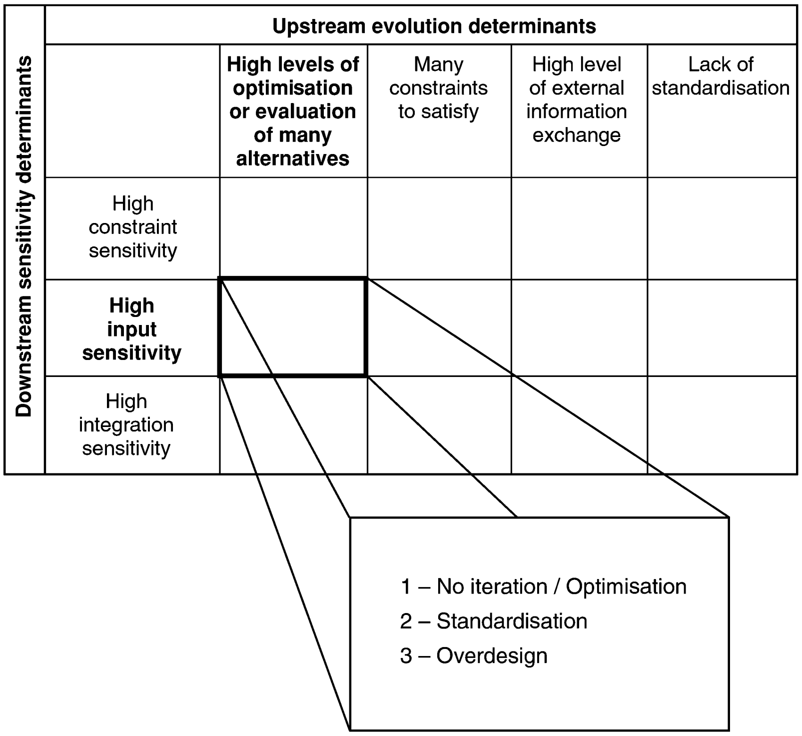

Figure 3 Example enhanced overlapping strategy framework for high levels of optimisation and high input sensitivity

flow rate to a downstream pump selection activity. The selection of the final pump is sensitive to the information received from the pipeline design activity. For example, the level of sensitivity of the pump selection activity may be high, if the selected pump is operating near the boundaries of its performance curve (referred to as 'constraint sensitive' under the determinants of sensitivity). In this case, a small change in information from the upstream pipeline design activity may result in significant rework (selection of an entirely different pump) for the downstream activity.

The third step in the decision algorithm is to determine possible overlapping strategies for each pair of dependent activities on the critical path using the information in Figure 1. For the above example (slow evolution–high sensitivity), the recommended strategies are overdesign, no iteration/optimisation, standardisation, set-based design or decomposition. The next step in the decision process is to further define the overlapping strategies and evaluate them based on resulting consequences (e.g. time savings, cost increase). Overlapping any pair of dependent activities has its own consequences regarding project costs, design costs and probability of design rework. The decision maker must select a strategy based on the amount of time savings possible and the consequential impacts to cost and rework. The overlapping decision is basically a trade-off between time savings and increased costs or rework. Typical consequences include increased costs due to the lack of design optimisation, increased levels of rework when preliminary information is used in the design, and increased materials wastage through overdesign. The final decision on which activities to overlap and what strategy to employ must be based on a comprehensive evaluation of the consequences and the detailed determinants of each activity pair.

Conclusion

Overlapping dependent activities is a logical approach for reducing project delivery time in a fast-track environment. Overlapping, however, should be approached in a systematic manner to reduce costs and risks. The overlapping strategy framework and decision algorithm presented in this paper comprise a practical approach to fast-tracking the design process that considers activity characteristics, overlapping strategies and project consequences in the overlapping decision.

The basic overlapping strategy framework considers the evolution and sensitivity characteristics of activity pairs to suggest appropriate overlapping strategies to reduce risks. The enhanced overlapping strategy framework builds on the basic framework by considering whether overlapping strategies act by speeding upstream evolution or by reducing the sensitivity of downstream activities to upstream information. The enhanced framework will provide project managers with additional information upon which to base their overlapping decisions.

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