Counterfactual Analysis of Sustainable Project Delivery Processes

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Abstract: Research is revealing that certain delivery process attributes influence the outcomes of sustainable construction projects. This preliminary research leads to follow-up questions such as which attributes are most influential? And how can the influence of these attributes be quantified? Answering questions like these is impractical using only traditional construction research methods. Delivery process attributes can have greater impact on one sustainable project and less on another, and controlling the numerous variables involved is nearly impossible. To answer questions facing similar constraints, economist Robert Fogel pioneered the counterfactual analysis research method, winning a Nobel Prize in the process. The objective of this article is to describe the adaptation and testing of counterfactual analysis to assist study of sustainable project delivery processes. Counterfactual analysis is especially well suited for sustainable projects, with their complex processes and stakeholder interactions. The adapted six-step method is informed by applications of counterfactual analysis in fields including economics, history, and political science. Descriptions of each step include specific examples from a pilot study of the method. A path forward is outlined for applying counterfactual analysis to examine key questions related to sustainable construction projects and to more broad areas of construction research.

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Introduction

Accounting for over one-third of all material and energy flows worldwide, the construction industry and its products contribute significantly to sustainability concerns related to energy and water resource shortages and global climate change (EPA 2007). These negative contributions represent both an opportunity and a responsibility for the construction research community. For instance, a proposal to reduce U.S. greenhouse gas emissions 50% by 2054 requires increased deployment of a portfolio of existing strategies across various disciplines (Pacala and Sokolow 2004). One of the strategies in this portfolio involves increasing the energy efficiency of buildings to a level that reduces the associated carbon dioxide emissions by about one-fourth. Increased deployment of the energy efficient building strategy will necessitate a greater market share of sustainable facilities, which seek to reduce the negative environmental impacts associated with the built environment. Construction researchers bear a responsibility to help our industry achieve these goals. Along with this responsibility comes a unique opportunity for construction researchers to assume a prominent role in the overall scientific research community by directly addressing key issues related to environmental sustainability.

Successful delivery processes (planning, design, construction, and operations) for sustainable projects are generally more complex and have more stakeholder interactions than delivery processes for their traditional counterparts (Hill and Bowen 1997; Reed and Gordon 2000; Lapinski et al. 2006). For example, while an architecture firm may work mostly independently on the schematic design for a traditional project, a sustainable project seeking to maximize energy performance requires a schematic design effort with coordination among a variety of groups such as construction professionals, mechanical engineers, facilities managers, building occupants, and utility companies. Other examples of delivery process attributes recognized as critical to sustainable projects are listed in Table 1. Researchers studying sustainable project implementation must negotiate these more complex processes as well as overcome standard constraints resulting from construction industry fragmentation and incomplete access to project data. Further, limited sample sizes are available for sustainable projects since most result in unique facilities, and on the rare occasion when facilities have the same physical characteristics, it is unlikely that the exact same delivery processes were used. Controlling for all of the potential confounding variables is practically impossible when applying experimental research to study sustainable project delivery processes. The counterfactual analysis research method offers a possible solution to this issue since it involves comparing an actual scenario to a hypothetical "counterfactual" scenario, thereby eliminating the need for large sample sizes (Fogel 1964).

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Table 1. Examples of Delivery Process Attributes Recognized as Critical to Sustainable Projects

Attribute and description	Project phase	Reference
Emphasize the owner's commitment to sustainability	Planning, throughout	Gould (2005)
Hold a design charrette at the beginning of design	Design	Kibert (2004)
Apply life-cycle assessment and energy modeling	Design	NIBS (2006)
Emphasize in bid documents the contractors' roles in sustainable project goals and documentation	Construction procurement	USGBC Research Committee (2008)
Require sustainability training for on-site workers	Construction	Deane (2005)
Involve building operators in the commissioning process	Operations, throughout	PGGGC (1999)

Objective

The objective of this article is to describe the adaptation and testing of counterfactual analysis to assist study of sustainable project delivery processes. This six-step method is influenced by previous applications of counterfactual analysis to construction research and to other more established research fields including economics and political science [Fogel 1964; Belkin and Tetlock 1996; National Institute of Standards and Technology (NIST) Editors 2002]. Designed to be straightforward and comprehensive, the adapted counterfactual analysis research method is tailored to work with available resources and references within construction industry organizations. The method was tested through its application to study the implementation of two recently completed sustainable projects. Each of the method's steps is described in general terms and then illustrated using an example from the case-study projects. Based on its application to study these projects, the counterfactual analysis research method is suitable for studying sustainable project delivery processes.

Counterfactual Analysis Research Method

Counterfactual analysis has proven valuable for answering questions such as "What is the impact of a national railway system on a country's economic development?" Or "What is the impact of poor interoperability on the cost of construction?" To answer the question concerning the impact of a railway system on the economy, Robert Fogel pioneered the use of the counterfactual analysis research method, comparing an actual scenario to a rigorously developed counterfactual scenario (Fogel 1964). Fogel won the Nobel Prize in economics for this research (Frangsmyr 1994). Using a version of this same method, NIST completed an influential study, measuring the cost of poor interoperability in the U.S. capital facilities industry at nearly $16 billion each year (NIST Editors 2002).

To adapt counterfactual analysis to research sustainable project delivery processes, background information is drawn from accepted applications of counterfactual analysis in other fields. This background information includes

- A definition of counterfactual analysis;
- Rationale for applying counterfactual analysis to study project delivery processes;
- Criteria for developing a rigorous counterfactual analysis; and
- Notable applications of counterfactual analysis.

Counterfactual Analysis Defined

In a counterfactual analysis, researchers think back in time to specify an independent variable of interest, the antecedent. The goal is to determine the effect that changing the antecedent has on a dependent variable, the consequent. Specifying connecting principles is essential, as the counterfactual analysis relies on these principles to link the antecedent and consequent. The validity of connecting principles is central to the validity of the counterfactual scenario (Lebow and Stein 1996).

Prior to exploring the application of counterfactual analysis to sustainable construction projects, an example of a straightforward counterfactual analysis helps illustrate fundamental concepts. In 2005, Penn State's football team finished the regular season with a record of 11 wins and 1 loss. Their only loss came at the University of Michigan in the seventh game of the season. A common counterfactual analysis used that season by Penn State students was some version of, "if Penn State had beaten Michigan, they would have finished the regular season undefeated." Here, the student creates the antecedent by going back in time and changing Penn State's loss against Michigan to a win. The student's expected consequent is that Penn State would finish the season undefeated. To realize this consequent, the student relies primarily on the connecting principle that the results from Penn State's games after the Michigan game would remain unchanged. This connecting principle is subject to argument since Penn State may have been overconfident in the following games had they beaten Michigan, or other teams may have been more motivated and prepared to play Penn State.

Rationale for Using Counterfactual Analysis

Counterfactual analysis offers a practical method for studying sustainable project delivery processes. Because no two projects are implemented exactly the same way, running experiments where hypothesized causes are manipulated while holding all other variables constant is impossible. This type of experimentation would require identifying projects similar to the project being studied but with different values of the variable under investigation. Even if these similar projects are identified, differences other than the variable being investigated would still exist. Addressing these confounding variables would require the use of statistical tools and gaining insight from the application of these statistical tools would require identifying a certain number of cases similar to the project being studied. For instance, if a $30 million, Leadership in Energy and Environmental Design (LEED)-Gold rated, architecture building on a University campus is studied, any proper statistical analysis would require projects that had comparable cost, function, and level of sustainability (LEED is the sustainable building rating system used by the U.S. Green Building Council). Most likely, no other building fitting this description exists, let alone enough cases to allow control for confounding variables. Even if these comparable projects did exist, major databases of sustainable projects currently contain very limited information on delivery processes [DOE 2004; United States Green Building Council (USGBC) Research Committee 2008].

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To illustrate the next point, assume that there are one million buildings similar to the $30 million LEED-Gold architecture building. In this case, statistical analysis is possible, but would still rely on implicit counterfactual assumptions that explanatory variables and error variables (e.g., location, date, and bidding climate) are uncorrelated (Fearon 1991). In an actual experiment, the use of random assignment would prove this assumption. In the statistical analysis of the architecture building, where random assignment is impossible, an implicit counterfactual analysis satisfies the assumption of no correlation. Implied in this statistical analysis is the counterfactual scenario that variables such as location, date of construction, and bidding climate are unrelated to project outcomes.

On the other hand, explicitly using counterfactual analysis to study this same architecture building is an attempt at an experiment where all variables except those under investigation are equal. The credibility of the counterfactual scenario relies on application of accepted theories separate from the hypothesis being tested, and on evidence of the facts relevant to the delivery processes for the architecture building. So, the primary difference between the statistical experiment and the explicit counterfactual analysis is not whether counterfactual scenarios are applied (Dawes 1996). Rather, both instances rely on counterfactual analyzes, and the primary difference is in how these analyzes are applied.

The Penn State football example helps illustrate this point. Assume researchers wish to determine whether Penn State would have beaten Michigan in 2005 were the game played at Penn State instead of at Michigan. Performing the statistical experiment requires identifying other instances where similar college football teams played against each other. Then, implicit use of counterfactual analysis determines which variables require control (e.g., location, team rankings, weather, injuries, and attendance) and which variables do not (e.g., the cheerleaders' uniform colors or the number of hot dogs sold at the game). This allows testing of the effect of home-field advantage on the game's outcome, and this effect is then compared to the impact identified for the controlled variables. Assuming enough cases were examined to satisfy the statistical requirements, the credibility for this experiment relies primarily on the implicit counterfactual analysis used to select the variables requiring control.

In contrast with the statistical experiment, a second option is application of an explicit counterfactual analysis. Here, the study for comparison is Penn State's 2005 game against Michigan with all variables equal except the location of the game, now played at Penn State. Using counterfactual analyzes to control for other variables is unnecessary, as these variables do not exist. Instead, the application of counterfactual analysis emerges when estimating the effect of home-field advantage on the game's outcome. The credibility of this explicit counterfactual analysis relies on the theory and facts used to support the estimated effect of home-field advantage.

Developing a Rigorous Counterfactual Analysis

As with other rigorous research methods, satisfying certain criteria adds to the credibility of results based on the counterfactual analysis. Six general criteria, outlined in Table 2, can assist evaluation of the credibility of counterfactual arguments (Belkin and Tetlock 1996).

General criteria fundamental to the development of all counterfactual analyses are clarity, logical, theoretical, historical, and statistical consistencies, and projectability. Openly defining the antecedent and consequent used in the counterfactual scenario satisfies the requirement for clarity (Belkin and Tetlock 1996). The logical consistency requirement is satisfied by precisely defining the principles connecting the antecedent and consequent to ensure that these principles do not contradict each other (Belkin and Tetlock 1996). The theoretical consistency criterion also addresses connecting principles, requiring that they match established theoretical generalizations (Belkin and Tetlock 1996). Theoretical consistency is enhanced by consulting existing literature and soliciting input from industry experts. Defining the antecedent to remain within the realm of possibility satisfies the historical consistency or "minimal-rewrite rule" (Belkin and Tetlock 1996). For instance, studying the cost savings possible if dinosaurs helped move materials for a modern-day project would fail the historical consistency criterion because the antecedent, dinosaurs helping with the project, would require a substantial rewrite of the history leading up to the antecedent. To satisfy the statistical consistency requirement, connecting principles between the antecedent and consequent are defined in accordance with established statistical generalizations (Belkin and Tetlock 1996). Finally, the projectability criterion is satisfied by separating out specific connecting principles from the counterfactual analysis to ensure real-world observations reflect these principles (Belkin and Tetlock 1996). Projectability can be addressed by consulting industry experts who did not participate in the implementation of the project being studied. This strategy provides independent evidence to confirm the connecting principles.

Table 2. Satisfying the Criteria for a Rigorous Counterfactual Analysis

Criteria	How satisfied
Clarity	Define the antecedent and consequent
Logical consistency	Define the connecting principles
Theoretical consistency	Define connecting principles in accordance with existing theory
Historical consistency	Define the antecedent to remain within the realm of possibility
Statistical consistency	Define connecting principles in accordance with accepted statistical generalizations
Projectability	Verify connecting principles on another scenario
Proximity	Minimize time and causal steps between the antecedent and consequent
Possibility of additional consequents	Consider negative and positive impacts of increased process transparency

In addition to the general criteria applicable to all counterfactual analyses, the proximity criterion, dealing with the distance between the antecedent and the consequent, is appropriate specifically for project delivery processes. Ideally, both the time and the number of causal steps are minimized between the antecedent and consequent (Fearon 1991). Time is an issue when applying counterfactual scenarios to historical questions where hundreds of years separate the antecedent and consequent. Time is of less concern when studying the implementation of construction projects, where the entire project typically spans less than 5 years. On the other hand, the proximity requirement to minimize the number of causal steps between the antecedent and consequent deserves careful consideration when studying project delivery processes. For example, increased collaboration during a building's design could lead to operations input, which leads to a change in the type of air conditioning system selected. This design change could lead to other impacts such as changes to windows, spaces, and structural systems. Accurately anticipating the

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Table 3. Details of Previous Influential Studies Applying Counterfactual Analysis

	Fogel (1964)	NIST Editors (2002)
Antecedent	A national railway system	Inadequate interoperabilty
Consequent	Impact on development of the United States	Costs in U.S. capital facilities industry
Data source(s)	Commodity output from 1839–1899 (Gallman 1960)	Interviews and surveys with 105 different industry stakeholders, U.S. census
Findings	The level of per capita income achieved by January 1, 1890 would have been delayed less than 3 months if railroads had never been invented	\$15.8 billion in interoperability costs measured in the capital facilities industry in 2002
Broad impacts	Explicit use of counterfactual analysis becomes an accepted research method in economics	Quantifiable evidence is provided supporting the need for improved integration in the capital facilities industry

effects of these changes in the completed project is impossible. Limiting the scope of the research project to examine one factor, such as costs, minimizes the number of causal steps while still permitting important insight into the impact of the increased collaboration.

The final criterion against which the counterfactual analysis is judged is recognition of the possibility of additional consequents. Introducing the antecedent may result in consequents in addition to the consequent under investigation (Lebow and Stein 1996). Additional positive consequents, such as improved customer satisfaction, would reinforce the consequent under investigation. On the other hand, additional negative consequents could outweigh the benefits realized in the expected consequent. For example, increased collaboration between competing organizations for the benefit of a specific project may compromise competitive advantage for these organizations. Researchers' consideration of additional consequents like these is essential to ensuring an accurate counterfactual analysis.

Notable Applications of Counterfactual Analysis

Counterfactual analysis has assisted rigorous research on subjects ranging from political science (Fearon 1991) to history (Winter 1986) to economics (Fogel 1964). Broad acceptance of counterfactual analysis resulted from its use in Nobel Prize winning research examining the impacts of railroads on U.S. economic development (Fogel 1964). Counterfactual analysis is now a research method of choice for researchers at leading U.S. institutions (Belkin and Tetlock 1996). In the construction industry, counterfactual analysis was integral to an influential study of the cost impacts of poor interoperability (NIST 2002). Illustrative details of two previous studies applying counterfactual analysis are provided in Table 3.

While no studies were identified applying counterfactual analysis specifically to study project delivery processes, description of NIST's interoperability study is worthwhile since it applied counterfactual analysis in the construction industry. By comparing actual cost impacts experienced to a counterfactual scenario with flawless exchange and availability of electronic information, this study conservatively estimates the annual costs of poor interoperability in the U.S. capital facility industry at nearly \$16 billion. Researchers arrived at this estimated cost impact by identifying interoperability impacts for 70 different organizations representing the primary stakeholders on construction projects. For example, architecture firms were asked how much time their employees spent transferring contractor requests for information to different file formats. Hourly wages were applied to convert this time to a cost impact, which was extrapolated to the national level using U.S. Census data.

Applying Counterfactual Analysis to Sustainable Project Delivery Processes

Counterfactual analysis offers a solution to issues constraining study of sustainable project delivery processes. However, the goals for application of counterfactual scenarios often differ between cases, so there is no standard methodology, which means counterfactual analysis must be adapted to study sustainable project delivery processes. This adapted method is presented in a step-by-step format, meant to support use of counterfactual analysis by others studying project delivery processes. The method's application to study recently completed projects shows that it is suitable for studying sustainable project delivery processes.

Case Studies—Process Transparency for Sustainable Project Delivery Processes

Counterfactual analysis adapted to sustainable project delivery processes was tested on Penn State's Stuckeman Family and Forest Resources buildings (Figs. 1 and 2). Specifically, the test study examined whether cost savings for sustainable buildings are possible through increased delivery process transparency. The complex processes for delivering sustainable projects are often unfamiliar to the stakeholders (e.g., owners, designers, and constructors) whose collaboration is essential to sustainable solutions. In other industries, process transparency helps facilitate

Fig. 1. Penn State's Stuckeman family building is an 111,000-square foot facility completed in August of 2005, which earned a LEED-Gold rating

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Fig. 2. Penn State's forest resources building is a 92,000-square foot facility, which earned LEED-Silver certification and was completed in January 2006

complex unfamiliar processes by making situations—including status, goals, and rules—visible to all stakeholders. So, improved process transparency would seem to reduce costs to deliver sustainable projects, but this hypothesis required empirical examination.

Counterfactual Analysis for Sustainable Project Delivery Processes

The step-by-step method for applying counterfactual analysis to study sustainable project delivery processes is shown in Fig. 3. In the following sections, each step of the method is described generally, including how the step contributes to satisfying the criteria for developing a rigorous counterfactual analysis (Table 2). Complementing the general descriptions, specific examples are provided for each step from the test-study of delivery process transparency.

Step 1: Map the Delivery Process

The initial step in applying counterfactual analysis to project delivery processes involves mapping the delivery process under investigation. Process maps show the activities and procedures of business entities as pictorial images, or "maps," that clearly convey information (Curtis et al. 1992). Mapping the delivery process is fundamental to developing a rigorous counterfactual analysis because the process map(s) allows the researcher to visualize the delivery process. This visualization assists subsequent steps of the counterfactual analysis, including location of the antecedent and consequent (Step 2), identification of connecting principles (Step 2), and revelation of cost impact records (Step 4). The required level of detail of the process mapping depends on the variables being examined in the counterfactual analysis.

Mapping the delivery process contributes to satisfying the historical consistency and proximity criteria for rigorous counterfactual analyses. The historical consistency criterion is addressed by ensuring that only the antecedent is changed from the actual delivery process. Because the actual and counterfactual scenario maps are identical with the exception of the changed antecedent, which is realistic, the counterfactual scenario remains within the realm of possibility. Mapping also contributes to satisfying the proximity criterion since locating the antecedent and consequent on a process map assists identification of causal steps between these variables.

Step 1 Example

Process maps were developed to study delivery processes for the Stuckeman Family and Forest Resources buildings using the Lean and Green (L&G) modeling protocol (Klotz et al. 2007). Maps showing the delivery process at a macrolevel, Level I and Level II maps, provided the necessary detail to satisfy Step 1. The Level I

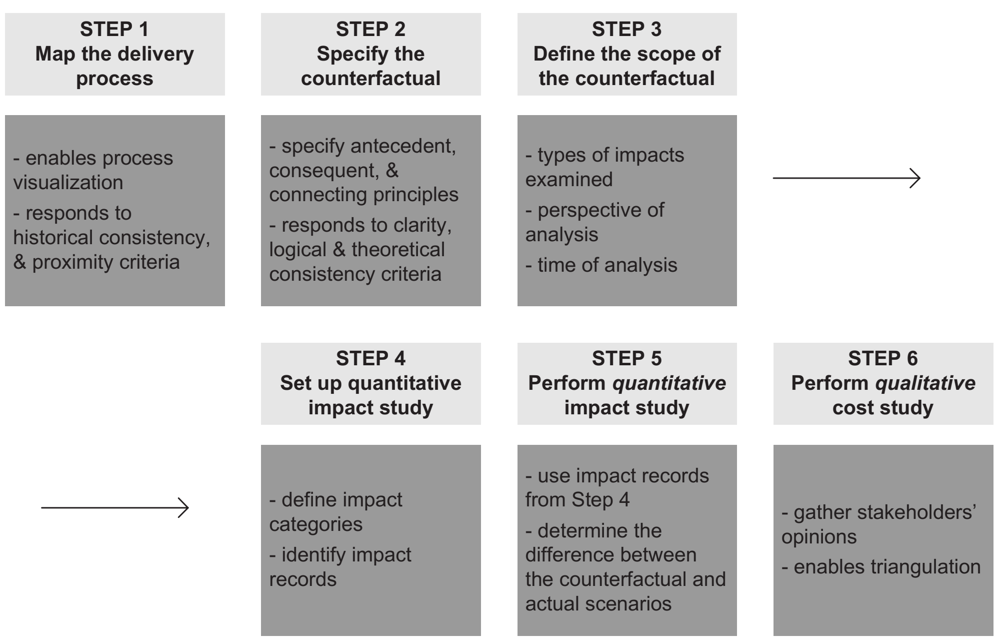

Fig. 3. Counterfactual analysis applied to project delivery

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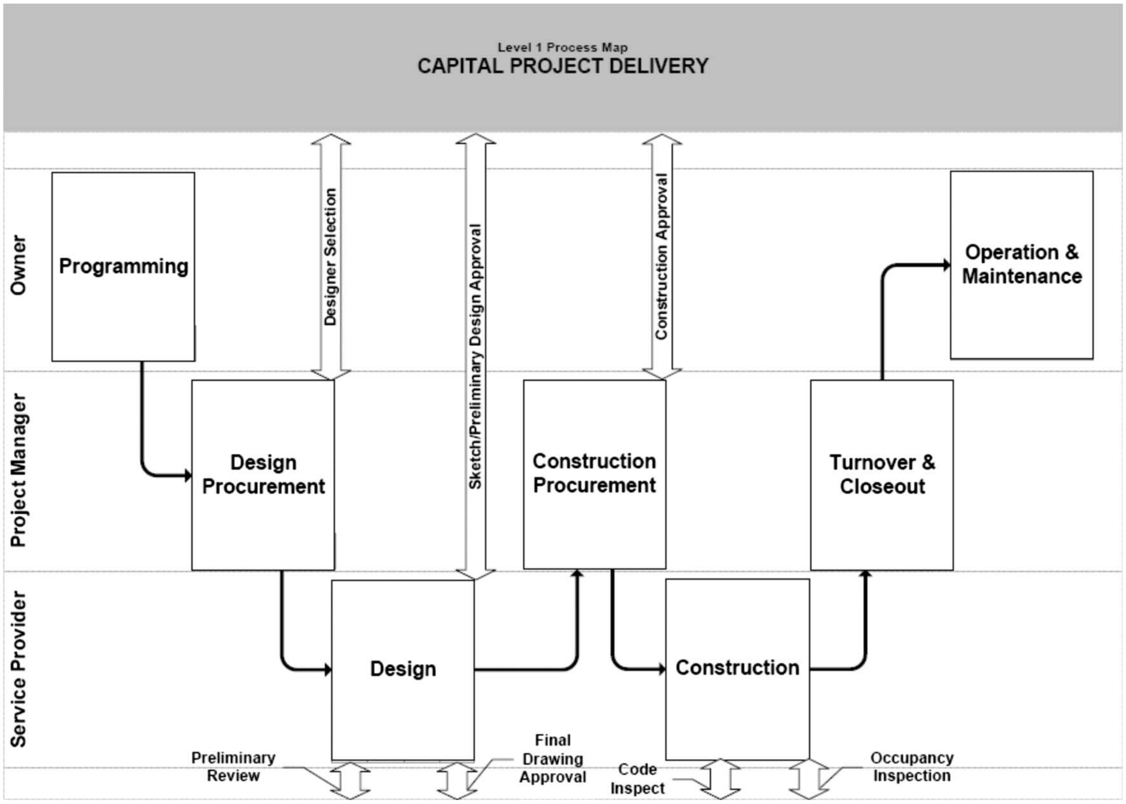

Fig. 4. Level 1 process map

map, representing an overview of the entire delivery process, is shown in Fig. 4. The remaining Level I and Level II maps are available online (Penn State Office of Physical Plant 2007), and detailed descriptions of the L&G protocol and map development are available to readers interested in process mapping methods (Klotz et al. 2007).

Step 2: Specify the Counterfactual Scenario

After mapping the delivery process, the next step involves clearly specifying the counterfactual scenario, including the antecedent, consequent, and connecting principles. Specifying connecting principles is one of several steps where iteration will probably be required. Researchers can hypothesize key connecting principles when first completing Step 2, but identification of additional connecting principles is likely when performing the quantitative cost analysis (Step 5). When practical, review of the counterfactual scenario by other researchers and industry members familiar with similar project types is encouraged. This helps ensure accurate specification of the antecedent and consequent and appropriate application of connecting principles.

Specifying the counterfactual scenario contributes to satisfying five of the criteria for rigorous counterfactual analyzes. Specifying the antecedent and consequent provides clarity, while specifying the connecting principles provides logical consistency. Possibility of additional consequents is addressed by hypothesizing unintended impacts that may result from the introduction of the antecedent. Theoretical consistency is addressed through the independent review of the counterfactual scenario. Finally, the projectability criterion is addressed by confirming connecting principles. A review of literature may provide this confirmation for broad well-established principles, such as the decreased level of influence on costs as a project progresses through planning, design, and construction (Paulson 1976). For more specific or less established connecting principles, consulting with industry experts familiar with similar projects is more feasible. Ideally, researchers confirm all connecting principles with significant impacts on the counterfactual analysis.

Step 2 Example

For the study of the Stuckeman Family and Forest Resources buildings, the antecedent and consequent result directly from the research question: "can complete process transparency lead to decreased sustainable project costs?" The antecedent is "complete process transparency," and the consequent is "sustainable project costs." Using the process maps developed in Step 1, the antecedent was introduced after capital planning and prior to the programming phase of each building's delivery process and the consequent was measured from the programming through turnover phases (Fig. 5).

The primary connecting principle for the test study limits consideration of cost impact consequents to when the information required to avoid the impact existed at the time the impact occurred, and when this information could have been accessed if there were perfect process transparency. This connecting principle prevents "Monday morning quarterbacking" by ruling out cost impacts resulting from a lack of process information as opposed to a lack of transparency of process information. For instance, during construction of the Stuckeman Family building, a fire resulted in damage leading to over $400,000 in change order costs. While certainly a significant cost for the sustainable project, at no point did any stakeholder possess information indicating that fire would damage the building during construction. Because the fire damage costs are not linked to the antecedent by connecting principles, these costs are excluded from the counterfactual analysis.

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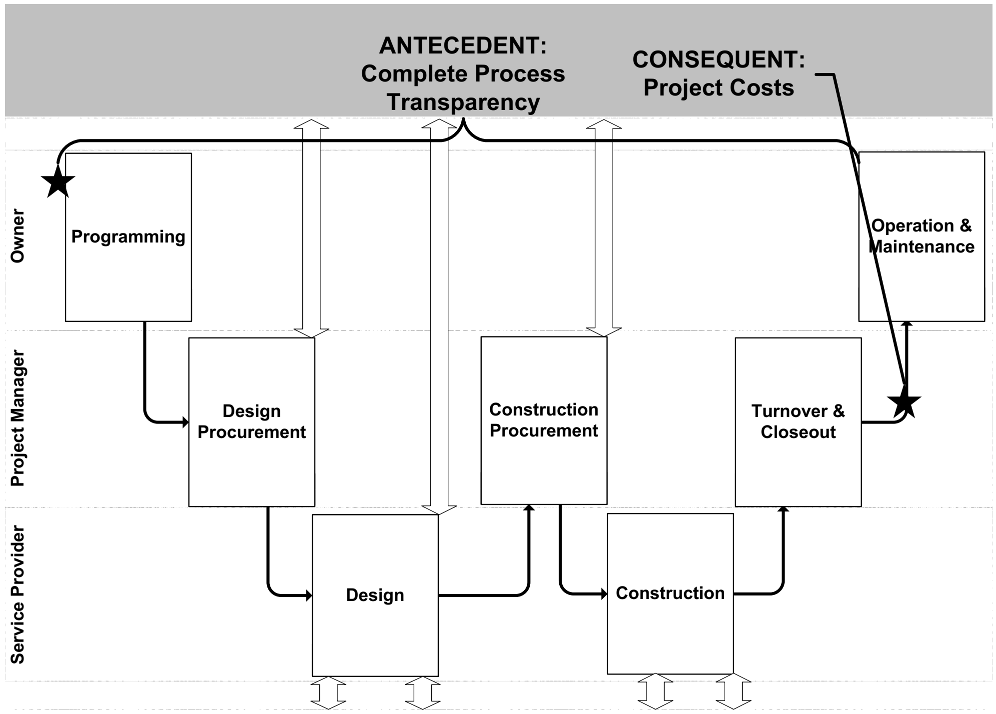

Fig. 5. Location of the antecedent and consequent in the Level 1 process map

On the other hand, a construction change order was issued on the same project to relocate a fire hydrant. In this case, the local fire department knew the correct location of the hydrant at the point during the design phase where avoiding the change order was possible. This location information could have been accessed with better process transparency, which could have been provided by a project stakeholder who understood the need to consult with the fire department on the hydrant location. However, the lack of process transparency resulted in a failure to identify the correct location until the construction phase, which resulted in a cost premium, which is linked from the antecedent using connecting principles and is, therefore, included in the consequent.

Several other connecting principles for the Stuckeman Family and Forest Resources counterfactual scenarios help define the magnitude of the consequent, sustainable project costs. These connecting principles, which are conservative to prevent overestimation of cost impacts, include

- Rework full cost: when rework resulting from a lack of process transparency is required, 100% of the cost of this rework is included in the consequent;
- Liquidated damages for cost of delays: the liquidated damage clause in construction contracts outlines the contractor's cost obligations for each day the project is late past the agreed upon completion date. The monetary amount of these clauses is often determined based on an estimated value of the beneficial use of the facility by the owner. This amount is therefore applied to estimate costs resulting from delays to the critical path in any phase of the project. For the Stuckeman Family building, liquidated damages were $2,000 per day, so when a lack of process transparency results in critical path delays, each day of delay is multiplied by $2,000 and 100% of this cost is included in the consequent. As long as these liquidated damages reflect costs associated with a breach of the contract completion time requirements, and the actual damages are difficult to determine, these liquidated damages are often enforced (Thomas et al. 1995; Hunts Point Multi-Service Center, Inc. v. Terra Firma Construction Management & General Contracting LLC 2003); and
- Change order premium cost: work associated with construction change orders costs more than the same work would cost as part of the original construction contract. For both of the test-study buildings, the contractor included a 5% markup for overhead and profit on contract work and a 10% markup for overhead and profit on change order work. Therefore, 5% of the costs of those nonrework change orders that could have been prevented with perfect process transparency are included in the consequent.

Step 3: Define the Scope of the Counterfactual Analysis

Step 3 involves defining the scope of the counterfactual analysis to further specify the antecedent, consequent, and connecting principles from Step 2. Scope aspects for definition may include types of impacts examined, perspective of the analysis, and time of the analysis.

When specifying the types of impacts for inclusion in the consequent, understatement of impacts is likely if only those impacts directly related to the antecedent are examined. However, accurately determining impacts that are indirectly related to the antecedent is difficult and including these impacts can reduce the credibility of the counterfactual analysis. For instance, increased employee satisfaction leading to more productive workers and decreased labor costs is one possible consequent of increased process transparency. However, this type of indirect consequent is difficult to quantify and relies on less-certain connecting principles (NIST Editors 2002). One solution is to consider only impacts directly related to the antecedent with the understanding that the total impacts are probably understated.

For project delivery processes, examination of the counterfactual scenario from the project owner's perspective is often appropriate as the owner ultimately experiences the majority of

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Table 4. Potential Impact Records for Counterfactual Analyzes

Project phase	Impact records
Programming	Meeting minutes, program, project schedule, and correspondence
Design procurement	Request for proposals, correspondence, and consultant contracts
Design	Charrette notes, review comments, consultant amendments, and correspondence
Construction procurement	Addenda, value engineering records, bid spreadsheet, bid requests for information (RFIs), meeting minutes, project schedules, and correspondence
Construction	Job conference reports, change orders, project schedules, correspondence, RFIs, inspection reports, and commissioning reports
Turnover and closeout	Job conference reports, punch lists, delay claims, correspondence, and training records

impacts. Consequently, defining the scope of the counterfactual analysis from the owner's perspective ensures that impacts identified reflect actual impacts borne by the project as opposed to impacts shifted from one group to another. To illustrate, a general contractor may save $50,000 by successfully arguing that moving the building occupants is someone else's responsibility. Despite the individual contractor's savings, the owner must now pay a different stakeholder to perform this work, so there is no overall benefit to the project.

Finally, researchers should consider the period of time for analysis when defining the scope of the counterfactual analysis. Depending on the research objectives, impacts may be examined for an entire project or for another period, such as 1 year or 1 month.

Step 3 Example

For the Stuckeman Family and Forest Resources counterfactual analyses, direct costs are calculated from the owner's perspective beginning with the planning phase and ending at the conclusion of the turnover phase (Fig. 5). The owner's perspective for examining cost reductions was chosen since owners typically make the final decision on whether or not to build sustainably. Only costs directly resulting from a lack of process transparency are considered. For instance, excluded from this analysis are costs associated with the decreased productivity of a project stakeholder who is frustrated by a lack of process transparency.

Step 4: Set up the Quantitative Cost Study

In Step 4, researchers identify impact records, which are hypothesized steps or points in the delivery process where impacts on the consequent are apt to appear. In addition to identifying impact records, characteristics are selected to filter, classify, and prioritize collected data. Step 4 and Step 5 are closely related, and several iterations may be necessary between these steps prior to moving to Step 6.

Selection of impact records depends on the counterfactual scenario specified in Step 2, and the process map(s) developed in Step 1 can help highlight expected impact records (see Table 4). A construction change order is one type of impact record, where impacts, in the form of costs, are explicit. However, impact records may also implicitly show impacts. For instance, meeting minutes from the design phase that reveal extensive discussion of an unclear process can be translated to a direct impact record by using an economic measure. Here, the appropriate economic measures are the meeting participants' hourly wages. Cost impacts are determined for this extensive conversation by multiplying the number of attendees at the meeting, the amount of time spent on the topic, and the economic measure.

Researchers' objectives for data analysis will guide their selection of characteristics to filter, classify, and prioritize their data. Relying on clear definition of the antecedent, filtering of data increases measurement reliability by helping researchers avoid measuring consequents outside the constructs of their project. Classification helps support the analysis of collected data. Researchers studying project delivery processes may choose to classify impacts by delivery phase, stakeholder impacted, delivery phase when the impact could have been eliminated, and more detailed attributes of the antecedent (NIST Editors 2002). Prioritization, or identifying when acting on the classifications is most beneficial, is integral to conclusions drawn from the data analysis. While not always possible, defining the filtering, classifying, and prioritizing characteristics prior to data collection reduces the probability of having to reprocess data.

Step 4 Example

Level I and Level II process maps were consulted to identify impact records for the Stuckeman Family and Forest Resources buildings. Because the cost impacts being studied are those related to process transparency, process maps were especially valuable for revealing where communication and interaction were required between stakeholders. Then, accessible cost records—including change orders, meeting minutes, contracts, and letters—were identified by reviewing project files and by consulting with project stakeholders. A Microsoft Access database was developed to assist with filtering, classifying, and prioritizing the process transparency costs identified in the impact records. Filtering of cost impacts helped to increase measurement reliability by ensuring that only costs associated with process transparency were included in the consequent.

Step 5: Perform the Quantitative Impact Study

In Step 5, the quantitative impact study is performed by calculating all of the impacts associated with the impact records identified in Step 4. Impact records determined to illustrate relationships between the antecedent and consequent are used to calculate the size of each impact. For instance, meeting minutes (the impact record) may highlight time and money resources (the consequent) spent resolving a problem caused by some phenomenon under investigation (the antecedent). Impacts from all of the impact records are then combined to represent the difference between the counterfactual scenario and the actual scenario. Two primary assumptions are required during this step.

The first assumption occurs when determining impacts. Project stakeholders are assumed to act in the best interest of the project. Behavioral factors, such as malice or laziness, might contribute to stakeholders' disregarding the antecedent, therefore eliminating or skewing any consequent. Not unique to counterfactual analysis, this issue could be addressed through a better understanding of behavioral influences on construction project stakeholders.

The second assumption occurs when combining impacts. Impacts are assumed as independent and, therefore, additive. This is not always the case during building projects where a mistake during design could lead to much greater costs during construction. However, many cost records already account for the interdependence between impacts. For example, contractors will include delay or resequencing costs in addition to time and material costs in their change orders. Further, as long as costs are not double counted, the assumption of independence is generally con-

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servative. Because costs increase as a project progresses, any interdependence not accounted for in the cost records would lead to a larger overall impact.

These assumptions contribute to the fact that, while counterfactual analyses can help determine the relationship between variables, it is not well suited to show definitively the magnitude of this relationship. For instance, the method will not support detailed conclusions, such as "increasing process transparency by 75% can decrease the costs to deliver a sustainable building by 10%." Assumptions can help ensure that cost impacts are the most conservative estimates, but counterfactual analysis remains best suited to research designed to develop, rather than test, theories.

Step 5 Example

The entire data set collected for the quantitative cost study of the Stuckeman Family and Forest Resources buildings is part of a separate article (Klotz et al. 2009). However, one example illustrates how the quantitative impact study was performed for the test study. For the locally harvested wood issue on the Forest Resources building, improved process transparency could have reduced sustainable building costs. The Pennsylvania Forest Products Association was involved during the design phase and supplied wood for the Forest Resources building, including over two linear miles of trim, rail, and casing, and over one-tenth of an acre of panels and ceiling. This locally harvested wood comes from nearby forests that have grown in size by 20% since 1995 [Pennsylvania Forest Products Association (PFPA) 2005]. Therefore, the wood is a relatively sustainable building material because it is a renewable resource and because required transportation and associated fossil-fuel use and emissions are minimized. During the construction phase, the timing of the wood products' availability on site was critical to enable completion of related work and maintain the project schedule. However, supply of the wood was based on the wood fabricators' production schedules. Materials were delivered to the site based on convenience to the fabricator rather than when materials were needed by the contractor. The importance of material delivery and sequencing of the construction process was not transparent to the Forest Products Association and the importance of the production schedule was not transparent to Penn State's project team. This situation resulted in approximately $175,000 worth of mitigation costs, which are reflected in change orders related to time extensions and additional labor costs due to out-of-sequence work.

Step 6: Perform the Qualitative Impact Study

In the final step of the counterfactual analysis applied to project delivery processes, qualitative data are obtained from project stakeholders to supplement the quantitative data from the project records. When both types of data support each other, showing similar impacts of the antecedent on the consequent, there is greater certainty in the results of the counterfactual analysis. Generally, design of instruments for collecting qualitative data (e.g., surveys, questionnaires, and interviews) should enable gathering of stakeholders' opinions of the antecedent's effect on the consequent. Obtaining data from multiple stakeholder groups contributes to a balanced view of this effect.

Step 6 Example

To qualitatively evaluate the counterfactual delivery processes for the test-study buildings, semistructured interviews were used to collect stakeholders' perspectives of the impact of process transparency on sustainable building costs. The semistructured format allowed the researcher to ask focused interview questions while remaining flexible to probe into more detail on specific areas of interest (Fellows and Liu 1997; Sociology Central 2007). Project stakeholders answered questions in the following categories:

- "Additional documentation" questions to ensure that entire sets of available information were not overlooked;
- "Additional information" questions to supplement incomplete information in the project records;
- "Cost impact verification" questions to confirm major cost impacts identified in the review of the project records; and
- "Connecting principles verification" questions to confirm connecting principles used in the research.

In each category, initial questions were posed and related follow-up questions were asked prior to moving to the next category. To reduce the chance of bias, where the interviewee is led to answers that confirm the findings of the researcher, the standard set of initial questions should be general and written without knowledge of the findings from the quantitative study. This could be accomplished by designing the questions prior to completing the quantitative study or by enlisting another researcher, unfamiliar with the quantitative results, to write the questions. After the initial questions are posed, the semistructured format allowed discussion and clarification of the answers provided by the respondent, while providing an opportunity for interview subjects to reveal costs related to process transparency that were not initially identified by the researcher (Sociology Central 2007).

Validity of Applying Counterfactual Analysis to Study Project Delivery Processes

Addressing the major categories of validity improves the likelihood that research conclusions based on the counterfactual analysis represent real-world facts (Trochim 2006). Conclusion, internal, external, and construct validity are addressed in the counterfactual analysis applied to project delivery processes. Still, researchers should be wary of threats to each of these validity categories.

- Conclusion validity requires a relationship between the antecedent and consequent. For instance, does increased process transparency influence the project costs? Threats to conclusion validity occur when there is insufficient evidence to relate the antecedent and consequent;
- Internal validity requires a causal relationship between the antecedent and consequent. Is it really a change to process transparency that is impacting project costs, or is some other factor at work? Threats to internal validity occur when changes to a variable other than the antecedent are causing the changes in the consequent. Correct application of counterfactual analysis requires that the antecedent under investigation is the only variable changed. Following this requirement ensures internal validity and eliminates confound variance, where outside variables cause changes to the consequent;
- Construct validity relies on how the antecedent and consequent are defined and operationalized to the counterfactual scenario. Is the counterfactual analysis set up to test the same "transparency" that was part of the original research question? A primary threat to construct validity is the failure to adequately define the antecedent and consequent in accordance with the research question under investigation. Completing Step 2 of the counterfactual analysis for project delivery processes increases construct validity; and
- External validity depends on how the results from the counterfactual analysis are generalized to other projects, which may include different people, places, or times. Will transparency

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and project costs have the same relationship for other sustainable projects? Researchers may choose to perform additional studies to account for these differences, demonstrate why these differences are not major threats to external validity, or qualify their conclusions accordingly (Trochim 2006).

Conclusions

This research has adapted and applied counterfactual analysis to study sustainable project delivery processes. The six general steps of the adapted method are provided with specific examples of that step's application to a test study of delivery processes for sustainable building projects. As in other research fields, project delivery process research relying on counterfactual analysis to *test* theories will be subject to justified scrutiny. Still, there is nearly unanimous agreement in these other fields that counterfactual analyses are valuable when applied to help *develop* theories (Weber 1996). As long as this distinction is considered, the adaptation and application described in this paper show that the counterfactual analysis research method is suitable for studying sustainable project delivery processes.

Limitations and Recommendations

The limitations of this research highlight two primary recommendations to strengthen future applications of the counterfactual analysis research method to study sustainable project delivery. First, the level of certainty in the Stuckeman family building and Forest Resources counterfactual scenarios would have improved with additional analysis of the antecedent, consequent, and connecting principles. Future applications of this method could improve certainty with another level of analysis by the primary researchers, or with independent analysis from other researchers and industry members familiar with similar project types. The second primary recommendation to strengthen future application of this method is to include a more systematic analysis of potential unexpected consequents in Step 2. Applying a process to list, rank, review, and address any unexpected consequents would help minimize the possibility that they invalidate the results.

Future Research

Studying the relationship between variables is a necessary step for a number of research opportunities related to the complex unfamiliar delivery processes required by sustainable projects. The case study discussed in this paper comes from a study examining whether improved process transparency can lead to lower costs for sustainable building projects. Counterfactual analyses may shed insight on related questions including which other delivery process attributes are valuable for implementation of sustainable projects? And, does improved delivery process transparency lead to projects with greater levels of sustainability? In addition, application of counterfactual analysis may provide insights into other key research opportunities related to sustainable project implementation, which include

- Developing a better understanding of facilities' impact on health and environment;
- Assessing impacts of indoor environment on human performance;
- Quantifying the impacts of daylight, lighting quality, and emerging electric light technologies on occupant health and performance; and
- Improving the understanding of the connections between specific project delivery systems (e.g., design/build and design-bid-build) and sustainability outcomes (USGBC Research Committee 2008).

Counterfactual analysis is well suited for studying delivery processes for sustainable projects, with their complex processes and stakeholder interactions. Counterfactual analysis may also be compatible to study other types of projects with complex and unique delivery processes including healthcare facilities, data centers, and product development processes. The continued application of counterfactual analysis to these types of research opportunities can yield important insights while refining the method itself for future use.

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