Measuring the impact of scale and coupling on solution quality for building design problems

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This paper presents the results of an experiment that measured human abilities to solve parameter design problems specific to the building design domain. The subjects of the experiment were university students who solved a series of parameter design problems that varied in terms of scale (number of design variables) and coupling (interactions between variables). Results show an exponential decrease in solution quality as the scale of the problem increases. Coupling has a comparable impact on solution quality for problems involving two to three variables, but becomes less significant as the scale of the problem increases. We discuss these findings in the context of information processing models for human cognition and explore the implications for current design theories and methodologies.

Keywords: design cognition, design theory, engineering design, information processing, parametric design

The design of contemporary Architecture, Engineering and Construction (AEC) projects involves the collaboration of many specialists. Typically these specialists are organized by discipline, with each discipline being responsible for the design of a particular component or subsystem of the complete project (e.g., structural system). These subsystems are often *coupled*, meaning that design decisions in one subsystem may influence or even control design decisions in the coupled subsystem (Marples, 1960). For example, the choice of beam depth for the structural system impacts the space available between floors to accommodate building services, and as a result, the HVAC system options available to the mechanical engineer. Coordinating design decisions within and between coupled subsystems has become a crucial responsibility of design managers, with important industry implications in terms of project quality and development time (Eppinger, Whitney, Smith, & Gebala, 1994).

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Researchers have developed a number of design theories and methods to help manage coupled parameter design problems. The Design Structure Matrix (Donald V. Steward, 1981; Steward, 1991) provides a method to analyze the coordination risk associated with coupled design tasks. Managers use this information to mitigate coordination risk by controlling team organization, task ordering and iteration. Coupling is also a central concern of the axiomatic design process (Suh, 1990). The independence axiom integral to this process states that designers should simplify the design task by creating an uncoupled problem. To achieve this end, designers are instructed to first create a matrix mapping functional requirements to design parameters and then to refine the parameterization of the problem to create a one-to-one mapping between design parameters (inputs) and functional requirements (outputs). It is in this context that Taguchi argues that coupling between design parameters should be minimized in order to improve the efficiency of the design process (Taguchi, 1986). All of these theories and methods acknowledge, in different ways, the negative effects of coupling on the design process.

Although the significance of coupling in design is widely acknowledged, the reason for its importance and the precise impact that coupling has on project quality has not been fully examined. Hirschi and Frey explored the conjecture that difficulties arising from coupling are due to human cognitive limits (Hirschi & Frey, 2002). They conducted a set of parameter design experiments involving human subjects that focused on the time required to achieve a particular level of solution quality for coupled and uncoupled problems of varying scale. The task chosen for the experiment had no real world context to avoid biasing the results with the subject's design expertise in a particular domain. Hirschi and Frey found that the time required for human subjects to complete *uncoupled* parameter design tasks scales linearly with problem size. In contrast, the completion time required for *coupled* parameter design tasks scales geometrically with problem size; roughly a threefold increase in the amount of time is required for each additional design variable.

This paper builds upon the work of Hirschi and Frey by addressing two important considerations that these researchers acknowledge is lacking in the design of their experiment, namely (1) subject expertise in the given problem domain, and (2) the subject's use of external problem solving aids (e.g., computer-aided design and engineering tools). In order to address these considerations, the scope of the experiments presented in this paper is limited to *well-defined* problems in the building design domain. A problem is *well-defined* if the design variables, objectives and constraints are known at the onset of the task (Eastman, 1969).

This paper is divided into four sections. Section 1 presents as background relevant research in the fields of cognitive science and design theory, including evidence that suggests that subject expertise and the use of external problem