

Can Design Improve Construction Safety?: Assessing the Impact of a Collaborative Safety-in-Design Process

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Abstract: This paper analyzes the impact of a large-scale safety-in-design initiative during the design and construction of a semiconductor manufacturing facility in the Pacific Northwest of the United States. Drawing on multiple data sources including individual interviews, group interviews, construction documentation, and an expert panel involved in the initiative, the writers identify 26 potential design changes on the project and assess the importance of timing, trade contractor involvement, and the type of design change in determining whether a proposed design change was ultimately integrated into the final construction plans. The writers further consider whether adopted design changes would have occurred in the absence of the safety-in-design initiative and whether the accepted design changes ultimately impacted construction site safety on the project. This analysis of a full-scale safety-in-design initiative provides important insights into how injury prevention efforts in the construction industry can begin upstream by involving designers, engineers, and trade contractors in preconstruction processes.

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Introduction

The notion that the safety of construction worksites can be increased through better design is both intuitively appealing and supported by research indicating that better planning, scheduling, and design could reduce hazards on construction worksites (Whittington et al. 1992; Suraji et al. 2001; Gibb et al. 2004). Recognizing the importance of these factors in construction worksite safety, the European Union enacted the "Control of Hazards on Temporary and Mobile Construction Sites" directive that requires member states to adopt national laws to formalize a process to ensure that construction site safety is considered during the design process. While implementation of the European Union directive has been uneven (Gibb 2002), this legislation has led to important safety-in-design efforts (Gibb 2004). However, a systematic assessment of the impact of these initiatives has yet to be done.

In the United States, by contrast, the current political and legal environment all but rules out any prospect of a safety-in-design requirement being enacted. Thus, despite the intuitive appeal of

safety-in-design, this idea is only likely to diffuse in the United States when owners, designers, and constructors see tangible evidence that safety-in-design processes lead to reduced risks on construction worksites. To this end, we assess the impact of an extensive safety-in-design process implemented during the design and construction of a large semiconductor manufacturing facility in the Pacific Northwest of the United States. Prior to presenting our analysis of the impact of this safety-in-design process, we briefly describe the field setting of this effort. A full description of this process and its development was presented at the *Designing for Construction Safety and Health Symposium* held in Portland, Ore. in September 2003 and is recorded in the Symposium's proceedings (Hecker et al. 2004).

Impact of Addressing Safety in Design

Assessments of the impact of addressing safety in design reveal considerable promise for the concept in reducing construction site injuries and fatalities. Studies of construction accidents and injuries suggest that a significant proportion of such events have their origins upstream from the building process itself and are connected to such processes as planning, scheduling, and design (Whittington et al. 1992; Suraji et al. 2001). One such analysis contends that 60% of construction accidents could have been eliminated, reduced, or avoided with more thought at the design stage (European Foundation 1991). A more recent study of 100 construction site accidents found that changes in the permanent design elements would have reduced the likelihood of the accident occurring in 47 of the accidents (Gibb et al. 2004). In a study of an intervention to prevent musculoskeletal injuries to construction workers, antecedents in design, planning, scheduling, and material specifications were likewise identified as probable contributors to working conditions that pose risks of such injuries during the actual construction process (Hecker et al. 2001). A

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recent study aimed at linking the design-for-safety concept to construction site injuries and fatalities found that the design was linked in approximately 22% of injury incidents and 42% of fatalities (Behm 2004). Lastly, 50% of the general contractors responding to a survey of the construction community in South Africa identified the design as an aspect or factor that negatively affects health and safety (Smallwood 1996). The contractors surveyed also ranked design the highest out of all components identified that negatively affect safety. The nature and complexity of construction site working conditions and processes make establishing specific cause-effect ties between design choices and safety and health incidents difficult. However, as these previous studies indicate, designers can have an impact on a significant number of injuries and fatalities by considering construction safety in their designs.

Reducing injuries and fatalities and improving worker health are not the only benefits associated with designing for safety. According to the Institute for Safety Through Design (ISTD), addressing safety in the conceptual or early design stages, rather than retrofitting the design to meet those needs, yields certain measurable benefits (Christensen and Manuele 1999; ISTD 2003). The ISTD lists the additional recognized benefits as: improved productivity, a decrease in operating costs, avoidance of expensive retrofitting to correct design shortcomings, and significant reductions in injuries, illnesses, environmental damage, and attendant costs.

The design and review process used influences the extent to which a design is successfully modified to impact safety. Well-planned and implemented design-for-safety review processes facilitate creating effective and efficient designs. Most of the previous studies quantifying the impact of the design on construction worker safety make a retrospective assessment of injury and fatality accidents. There is also a compelling need to better understand how to put the safety-in-design concept into practice.

Field Setting and Safety Environment

Intel Corporation initiated a safety-in-design process early in the programming phase of a \$1.5 billion semiconductor fabrication and research facility, commonly referred to as a "fab." This particular fab, designated as "D1D," was intended for the development and manufacture of Intel's most advanced semiconductors and was projected to have over one million square feet. Like other fabs, D1D required extensive electrical, mechanical, and process piping engineering and construction. Approximately 3.3 million construction labor h were required for its construction and, during periods of peak construction, there were over 2,400 craft workers on site.

This safety-in-design program at D1D was impressive both in its scope and ambition, and the name life cycle safety (LCS) was chosen to reflect this. One notable distinction of this program was its aim to extend the concept of safety-in-design to reflect safety concerns in all phases of the facility's lifecycle including programming, detailed design, construction, operations and maintenance, retrofit, and decommissioning. In this way, the LCS process sought to address health and safety issues for multiple stakeholders including construction workers, tool (equipment) installers, maintenance workers, and operators of the fabrication facility. Furthermore, the Intel task force with responsibility for creating LCS chose not to include the word "design" in the program's name so as not to shift the entire burden for safety to the designers of the facility. Rather, LCS was envisioned to

be a comprehensive review process to include the owner of the project, the design firm, the general contractor, and the numerous trade contractors involved in the construction and operation of D1D.

A safety-in-design task force was charged with developing a process that would increase the focus in the design stage on safety issues in construction and subsequent building phases and would bring trade contractors into the planning and design process. Membership of the task force included representatives of Intel, the design firm (IDC), and the contractor serving as the construction manager on D1D (Hoffman Construction). A third-party consultant also served on the task force and facilitated the process. Subsequently, seven discipline-based workgroups evaluated design options against a plan of record, which in this case was a prior fab constructed at the same Oregon campus, and a similar facility in another state. Work groups, in turn, reported programming decisions to the Design Review Task Force that assessed these recommendations based on a number of criteria including cost, schedule, energy consumption and environmental emissions, adaptability for future manufacturing technologies, and improved safety through design. The LCS continued during the detailed design phase, in which trade contractors provided input on the 22 design packages created for D1D's construction. These packages were subject to a technical review and an LCS review, the latter distinctive to D1D and the LCS process.

The involvement of Hoffman Construction and trade contractors in the programming phase was an important element of LCS, and the terms of their involvement underscores the distinctiveness of this effort. Without guarantees that it would be awarded a contract to be the Construction Manager on D1D, Hoffman agreed to provide input into the design during the programming phase under a preconstruction services contract. Likewise, while they were compensated for their time for participation in disciplined-based workgroup meetings, trade contractors had no guarantee that they would be awarded construction work on D1D. No doubt Hoffman and participating trade contractors saw their participation in the programming phase as an opportunity to learn more about D1D and the likely scope of work, and viewed both as information that would increase their probability of winning future construction work on D1D. Thus, while D1D utilized a design-bid-build delivery model for subcontract work, the interaction among trade contractors and designers in the early phases of the project was in many ways more typical of what might be possible in a design-build delivery model.

As this was a significant new process for Intel, the company invited researchers from the Univ. of Oregon and Oregon State Univ. to facilitate, observe, document, and evaluate LCS. Members of this research team had been involved in earlier health and safety research at this Intel campus. Researchers attended meetings of the LCS task force and all significant meetings and training sessions related to the implementation of LCS. The research team also had access to all but the most confidential documents used in the design process and the safety-in-design effort.

Research Questions

In this paper, we address a number of questions related to the impact of the LCS initiative on design changes in the programming and detailed design phases of D1D:

1. To what extent does the timing of a suggestion for a design change determine whether a design change suggestion is implemented?

2. How does the involvement of trade contractors impact whether a design change suggestion is implemented?
3. To what extent does implementation of a design change depend on the broad category of risk addressed in a design change recommendation?
4. Would observed design changes on D1D have occurred in the absence of LCS?
5. Did design changes resulting from LCS lead to reduced safety and health risk to construction workers on D1D?

The first three questions explore the relationship between the timing, origin, and nature of proposed design changes and the likelihood of implementation of design changes on the project. Answers to these questions may suggest areas for further refinement of this safety-in-design effort and implementation of other safety-in-design processes on future projects. The fourth question attempts to determine whether the safety-related design changes identified on D1D would have occurred in the absence of the LCS process. In addressing the final question we make a preliminary assessment as to whether the observed design changes created a safer environment for construction workers on D1D.

Research Methodology and Data Sources

To address these questions, we followed the guidelines proposed by Huberman and Miles (1994) for managing and analyzing large quantities of qualitative data. Specifically, Huberman and Miles recommend that to maximize transparency and replicability of the analysis, researchers can create a database of items to be included in the analysis. Where possible, they suggest using multiple data sources, including raw documentation related to the analysis, to backfill empty fields in the database. Consistent with this, we created a database of various design changes or missed opportunities for design changes on D1D. Each entry in the database contained:

1. A description of the proposed design change;
2. The places where the issue was raised in the LCS process (i.e., safety checklist, programming, detailed design, technical review);
3. Which stakeholder proposed the change;
4. The safety concern addressed by the proposed design change (e.g., material handling, material substitution, fall protection, access, construction process); and
5. Whether the design change was implemented.

To identify implemented and unimplemented safety-related design changes, we initially convened an expert panel consisting of three key LCS participants, and we asked them to identify all cases "where the LCS process identified or missed an opportunity to enhance safety through a proposed design change." Two members of the panel had been part of the LCS task force—the Hoffman safety and health manager for D1D and the task force facilitator, a safety and ergonomics consultant. The third member of the expert panel was an engineer working for Hoffman who served as one of three facilitators of LCS reviews and was therefore intimately familiar with the design review process for all packages. This team initially identified 15 cases of which nine were either fully or partially implemented in the design and six were not implemented. Following this, our university research team identified an additional 11 cases (seven implemented and four not implemented) by comprehensively mining all available LCS documentation. The following data sources contained specific information regarding where in the process the design

change was recommended, who recommended the design change, and the safety issue addressed by the design:

Safety-in-Design Checklist

Based on lessons carried forward from earlier projects, the design firm developed a 101-item safety-in-design checklist. These items consisted of design issues identified as potential problem areas for the construction and/or operation of the D1D facility. IDC developed the checklist as an interactive and open-ended tool for designers. The safety-in-design checklist, though part of the LCS process, was not unique to LCS insofar as a safety checklist had been used on earlier Intel construction projects.

Programming Focus Group Interviews

As one of its early activities, the LCS taskforce organized six focus group interviews during the programming phase composed of trade contractors (four trade groups), Intel facility technicians, and vendor tool technicians who had worked on previous fab projects at Ronler Acres. The LCS task force members, working with members of the university research team facilitated these group interviews, with four to six informants at each session. Comments provided during the focus groups were coded according to design discipline: structural/architectural, mechanical, electrical, or piping. The interviews were recorded and transcribed, and analysis of these transcripts identified 196 distinct comments related to safety-in-design. These focus group interviews were unique to the LCS process insofar as they were not conducted on earlier Intel construction projects.

Life Cycle Safety Review Comments

The LCS review involved Intel maintenance technicians, trade contractors, and environmental safety and health staff, and focused specifically on issues related to safe design. The review of the 22 design packages produced 789 design review comments, and included: the date of origin of the comment; drawing reference page/sheet number; whether trade contractors, Intel maintenance employees, or environmental and health and safety specialists provided the comment; the designer responsible for the design scope addressed by the comment; the comment and action required as suggested by the reviewer; and the resolution and action taken by the IDC package owner. Detailed design reviews were a distinctive and integral part of the LCS process. The detailed design reviews provided a mechanism for various groups involved in the construction of D1D to address safety over the life cycle of the facility, and the extent and level of interaction provided by the detailed design review process had no analog on previous Intel construction projects.

Technical Review Comments

Technical reviews have been a common feature on all fab construction projects at this and other sites. Intel and designer personnel regularly conduct these reviews to verify and improve the technical characteristics and qualities of the design. The technical review database consisted of 7,071 review comments with information similar to that provided by the LCS review comments. We included these comments in our analysis to determine what design changes might have occurred in absence of the LCS process.

Table 1. Life Cycle Safety Cases

Number	Case	Description
1	Utility level below subfab	Provide a full basement utility level below the subfab instead of just a utility trench.
2	Subfab ceiling height	An increase in the subfab story height by 9 in. in order to prevent “headknocker” hazards when walking along the extensive system of catwalks throughout the subfab.
3	Welded truss connections	Redesign of the steel trusses to have welded connections that could be made off site.
4	Mechanical restraints	Specify mechanical restraints instead of concrete thrust blocks at changes in direction of underground utilities.
5	Utility corridor site package delay	Sequence the letting of the utility corridor site design packages to permit safe excavation of utility trenches amidst all of the other surrounding work on the structure of the facility.
6	Floor coating below raised metal floor	Utilize a floor coating below the raised metal floor in the fab which creates less friction and permits easier movement when crawling across the floor.
7	Conduit sweeps	Specify fiberglass sweeps for electrical conduit instead of steel sweeps.
8	Cooling tower access	Provide permanent access to elevated cooling towers for installation and maintenance of motors.
9	CLX cable	Specify lighter weight electrical cable inside conduit instead of heavy, insulated cable.
10	Trestle walkway	Provide permanent fall protection along the trestle walkway for use when accessing the trestle.
11	Parapet height	Design parapets to be 42 in. tall to act as guardrails during construction and future roof maintenance.
12	Fall protection—anchorage points	Design in permanent anchorage points at specific locations in the facility for connecting lanyards and safety lines.
13	Fall protection—general	Provide permanent fall protection measures (anchorage points, guardrails, etc.) throughout the facility.
14	Blast gate access	Provide safe access to the operating equipment used to open and close the large blast gates.
15	Brace connections	Modify cross brace connections to shop welded connections and make the weld areas more accessible and simple to erect.
16	Center-build	Accommodate a construction sequence involving building the facility from the center out in two directions.
17	Material/personnel access	Design height and swing of doors, and emergency shower stalls, to permit safer passage of materials and equipment.
18	Slow response to requests for information	Ensure efficient and timely response by the designers to constructor requests for information.
19	Utility rack access	Provide permanent access to upper utilities on all utility racks.
20	Column gridline coordinates	Clear and accurate posting of the column grid lines at each column to allow workers to quickly orient themselves to their surroundings.
21	Adequate power supply	Design of the permanent electrical system to be available for use, and provide adequate power supply, during construction.
22	Reduction of noxious fumes	Specify materials for primers, sealers, and other coatings that do not emit noxious fumes.
23	Better lighting	Design permanent lighting that can be installed and used during construction, and which provides adequate light in both interior and exterior work areas.
24	Identification of power sources	Use consistent coding of power sources (using color, text, or some other identifier) throughout the project.
25	Ground pads	Provide electrical ground pads at each column base to ensure tie in to grounding grid.
26	Walkable ceiling	Design the ceiling above the fab level to support construction personnel working in the interstitial mechanical area above.

Exit Focus Group Interviews

The LCS task force conducted 28 exit focus group interviews with general foremen and field superintendents from trade contracting firms after they completed their work on the project. These contractors represented over 90% of the construction man-

hours on the project. A 29th focus group included safety personnel from the project. From the notes of these group interviews, 464 comments on various aspects of safety and design on DID were identified.

Where further information or clarification was needed, the re-

Table 2. Importance of Input Early in Project ($n=26$)

	Design change not implemented	Design change implemented
Design change not noted in programming phase	5	4
Design change noted in programming phase	5	12

search team consulted with the expert panel and with other design and construction personnel who had been directly involved in the case in question. Table 1 contains a list of the 26 cases along with a short description of each.

This set of cases is subject to a number of potential biases. First, our methodology likely leads to an understatement of the impact of LCS on design changes. As can be seen in Table 1, a number of “cases” such as better lighting (Case number 23) and fall protection (Case numbers 12 and 13) likely led to multiple design changes throughout the facility. Second, the nature of the exit focus groups with trade workers highlight changes that were not implemented and did not surface a number of implemented design changes. What workers and contractors tend to remember at the conclusion of projects are aspects of the design that created hazards; less salient are changes that reduced risks. Finally, although our methodology likely undercounts the number of actual design changes made, the design changes we identify may not be a consequence of the LCS process since multiple factors and design processes at Intel could contribute to changes in the design.

Data Analysis and Results

The compilation of the case database allowed the research team to conduct a path analysis of each of the 16 implemented and ten unimplemented proposed design changes. For each identified case, representative keywords were used to electronically search for mention of the case in each of the data sources. When reference to the case was found, identification of who raised the issue was made, i.e., whether it was a trade contractor or other project team member. By organizing the different data sources in chronological order, a temporal pathway through the data sources was then developed for each case. For example, Case number 2 involved an increase in the subfab ceiling height by 9 in. in order to prevent “headknocker” hazards when walking along the extensive system of catwalks throughout the subfab. A general statement to eliminate this type of hazard throughout the facility was included in the safety-in-design checklist. During the programming phase, both trade contractors and others involved in preliminary reviews of the plan of record identified the low ceiling height as a hazard and recommended an increase in height. As the project progressed through design, no mention of the subfab ceiling height was made in the LCS reviews or the technical reviews. Based on the recommendation made during programming, however, the design suggestion was implemented and ultimately identified as a success by those interviewed in the exit focus groups at the end of construction.

Timing of Suggestion and Likelihood of Implementation of Design Change

Establishing a path through the data sources for each case permitted an evaluation of characteristics that influenced whether the design suggestion was implemented. One factor evaluated was the

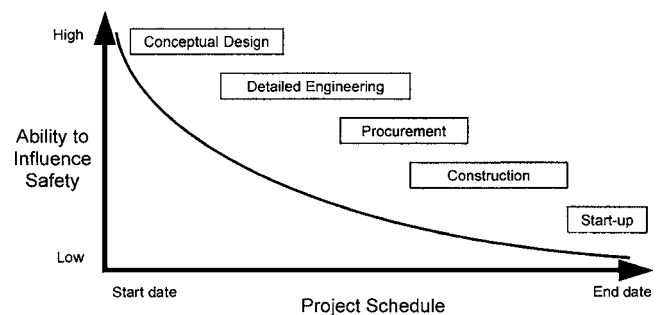


Fig. 1. Project schedule versus ability to influence safety [adapted from Szymberski 1997]

timing of the design suggestion. Table 2 shows the distribution of suggested design changes according to whether they were noted in the programming phase and implemented. The table shows that 12 (71%) of the 17 design changes that were noted in programming were implemented. By contrast, of the nine design changes that were not noted in programming but raised later on in the project, only four (44%) were implemented. Reasons for the decreased likelihood of design changes proposed later being implemented include: high capital costs associated with implementing the change later in the design; a lack of information regarding the impact on worker safety and health; and the particular market forces associated with rapid obsolescence in the semiconductor industry, driving the completion of the project as early as possible without any delays.

Certain cases illustrate the importance of timing. Early design proposals that were implemented include floor coating below raised metal floor (Case number 6), anchorage points for fall protection (Case number 12), general fall protection (Case number 13), provision of column gridline coordinates (Case number 20), and better lighting on construction site (Case number 23). By contrast, conduit sweeps (Case number 7), blastgate access (Case number 14), material/personnel access (Case number 17), and adequate identification of power supplies (Case number 24) are examples of potentially good suggestions that were not raised in programming and were not implemented. These results are consistent with the notion that recommendations for design changes are most likely to be implemented when presented early in a project, and complements the belief that there is a greater ability to influence safety on a project earlier in the project as illustrated in Fig. 1 (Szymberski 1997).

While our data analysis supports this general trend, we should note that there are important counterexamples of design changes that were raised only in the detailed design phase of the project that were eventually implemented. These include the use of mechanical restraints (Case number 4), minimum heights for parapets (Case number 11), and the provision of ground pads (Case number 25), though with the exception of Case number 4, these are relatively uncomplicated changes. More generally, for some basic structural features of DID, early decisions are not very revealing about the general importance of timing and the likelihood of implementation of design changes. Such is the case with the utility level below the subfab (Case number 1) and the subfab ceiling height (Case number 2). In both these instances, these design changes were so fundamental to the structure that they could only be implemented in the early phase of a project's design.

Table 3. Importance of Trade Contractor Input Early in a Project ($n=26$)

	Design change not implemented	Design change implemented
Design change not noted by trade contractor (but either noted solely by others or not noted at all) in programming phase	8	5
Design change noted only by trade contractor, or by trade contractor and others, in programming phase	2	11

Contractor Involvement and Likelihood of Implementation of Design Change

Another factor considered as having bearing on the implementation of a suggested design change was the involvement of trade contractors. Working in the field with the construction equipment and materials on a daily basis provides unique insight into the safety hazards to which the workers are exposed. Using the knowledge gained through this experience, trade contractors are able to pinpoint significant design impacts that may be overlooked by designers, and their input is perhaps regarded as coming from a more highly qualified source. During the LCS process, trade contractors provided input during both the programming and detailed design phases. We assessed the impact of trade contractor input during programming by assessing how many of the cases that were noted by trade contractors in programming were also implemented. As shown in Table 3 11 (85%) of the 13 design changes suggested in programming by only trade contractors or by both trade contractors and others, were implemented. These include the following:

1. The use of welded connections on the steel roof trusses (Case number 3). The effects of truss constructability were raised by trade contractors during work group sessions in programming. It was felt that redesigning the steel trusses to have welded connections constructed entirely off site would not only be safer, but more feasible and economical as well. This change reduced the cost and weight of the trusses, allowed for prepainting off site, and reduced the touchup painting required in the field. With respect to safety, it reduced on-site labor hours and the risk associated with making steel connections at elevation. The final product was also felt to be of higher quality than the bolted trusses used on previous fab projects.
2. Alternative floor coating beneath the raised metal floor (RMF) on the fab level cleanroom floor (Case number 6). The floor coating used on the cleanroom floor of previous fabs was of such a rough texture that it did not permit easy movement under the RMF to route utilities, a task which can be especially difficult because of the need for workers to wear full protective gowns ("bunny suits") while working in the cleanroom. For D1D, the floor coating specification was changed to reduce friction and permit easier movement. While the LCS process was successful in exposing this ergonomic problem and leading to a design change, the new coating did not work as well as planned and ease of movement was not necessarily improved.
3. Providing column grid line coordinates within view throughout the fab (Case number 20). On previous fab projects, due to the large size and complexity of the facility, workers had difficulty orienting themselves to where they were located in the fab. This was of concern because they were unable to

Table 4. Importance of Trade Contractor Input during Programming and Design ($n=26$)

	Design change not implemented	Design change implemented
Noted by others in programming or design	4	1
Noted by trade contractor in programming or design	1	5
Noted by trade contractor and others in programming or design	3	10
Not noted in programming or design	2	0

direct emergency response without known locations. Clear and accurate posting of the column grid lines at each column in D1D allowed the workers to orient themselves to their surroundings.

4. Designing the electrical system to provide adequate power supply during construction (Case number 21). Trade contractors made suggestions during programming and in the LCS and technical reviews to facilitate the adequacy of electrical power during construction. In response to these suggestions, electrical box connections were provided to supply permanent sources for construction power. While permanent power sources were present, there was not sufficient coverage over the entire facility, including under the RMF and in the interstitial area.

Of the 13 design suggestions not noted in programming by trade contractors, only five (39%) were implemented. The conduit sweeps (Case number 7) mentioned previously is an example of a design change that was not noted by trade contractors in programming and not implemented. By the time this was raised as a material handling problem in the field, it was too late to change the specification from steel to fiberglass, and there was no consensus that fiberglass would stand up to the cable running through it. Another example is the identification of power sources (Case number 24). These results suggest that the design changes are more likely to be implemented if noted by a trade contractor, and underscore the need for bringing construction knowledge into the safety-in-design process.

We also evaluated trade contractor input throughout the project as it compares to input from others involved in the LCS process. Table 4 shows the distribution of the cases according to who raised the issue and whether the design change was ultimately implemented. Others besides trade contractors who brought up design suggestions included representatives from the designer (IDC), Intel, and the construction manager (Hoffman). When noted by only the trade contractors, or noted by trade contractors and others, the data suggest that the design change is more likely to be implemented. Implementation occurred in 15 out of the 19 cases (79%) in which trade contractors provided input. On the other hand, four of the five design changes (80%) noted only by others were not implemented. Other examples are the need for permanent access to elevated cooling towers for installation and maintenance of motors (Case number 8), and the use of materials for primers, sealers, and other coatings that do not emit noxious fumes or vapors (Case number 22). This result suggests that trade contractors provide valuable input in design and programming and, to a certain extent, other project team members rely on trade contractors for practical advice on how to modify the design to make it safer to build.

Table 5. Implementation of Design Changes by Type of Issue Addressed ($n=26$)

	Design change not implemented	Design change implemented
Access	4	9
Fall protection	1	4
Materials/material handling	2	2
Construction process	2	1
Material substitution	1	0

Category of Suggested Change and Likelihood of Implementation of Design Change

While each of the cases relates to a different aspect of the design, they can be categorized according to one of five different broad safety and health issues: access, material handling, fall protection, material substitution, or construction process. Based on a general review of the cases, these issues were felt to capture the primary safety and health emphases of all of the cases. Each of the cases was categorized according to the type of safety and health issue addressed, and a comparison made regarding whether the suggested change was implemented in the design. The relationship between implementation and safety and health category for the cases is shown in Table 5.

The most common type of design changes (50%) were those aimed at improving access to the work. Those changes that permitted unobstructed, unconfined, or more efficient access to perform the work, including allowing the work to be conducted off site rather than under jobsite conditions, are included in this category. These cases range from including a utility level below the subfab (Case number 1) to minimize congestion, to those design changes intended to eliminate obstructions to the work, such as the welded truss connections (Case number 3) and brace connections (Case number 15). Also included are design changes intended to permit safe access to the work when fall, lighting, emergency response, or other safety hazards exist that impact access (e.g., Case number 8—cooling tower access; Case number 14—blast gate access; Case number 19—utility rack access; Case number 23—better lighting; and Case number 20—column grid-line coordinates).

Fall protection was addressed in five of the 26 cases (19%). The cases in this category are distinguished from those coded as “access” in that the primary intent of these is to improve or provide fall protection. Some of the cases listed in the access category protect against fall hazards as well, but their intent was interpreted as primarily facilitating access to the work. Increasing the parapet height to 42 in. to provide a guardrail during construction and future roof maintenance (Case number 11) is in this category, along with providing fall protection anchorage points designed into the structure in specific locations (Case number 12) and generally throughout the facility (Case number 13). Providing fall protection along the trestle walkway (Case number 10) and designing the ceiling above the fab level to be walkable (Case number 26) so that workers do not have to tie off for fall protection while working in the interstitial space, are also in this category.

The material handling category denotes those design changes aimed at improving the ability to move material around the jobsite and manipulate it during erection or installation. Improvements in ergonomics and reductions in strain and sprain injuries are the expected results from implementation of these changes. Four of the 26 cases (19%) were listed in the material handling

category. Examples of these types of cases are: using mechanical restraints instead of thrust blocks at changes in direction of underground utilities (Case number 4); specifying fiberglass conduit sweeps instead of steel sweeps (Case number 7); and using lighter weight electrical cable inside conduit instead of heavy, insulated cable (Case number 9).

Only one case was in the substitution of materials category (Case number 22), but this is a category worth including because it encompasses many industrial hygiene issues. This is likely to be a category in which changes were made that may not have been picked up by our analysis.

The fifth category, construction process, includes those design changes that impact the way that design process and the designer–constructor interface impact the construction process and the constructor’s planning and coordination of the work, as opposed to the physical aspects of the design itself. Three cases (12%) fit into this category. One suggestion was to sequence the letting of the utility corridor site design packages to permit safe excavation of utility trenches amidst all of the other surrounding work on the structure of the facility (Case number 5). The decision to build the facility from the center out in two directions and the design impacts associated with this construction sequencing (Case number 16) was also in this category. Finally, efficient and timely response by the designers to constructor requests for information (Case number 18) was considered a construction process issue.

The findings suggest that design suggestions related to material handling, which were implemented in only two of the four cases (50%), may be more difficult to implement. This is perhaps a reflection of designers not understanding how material is moved and manipulated during construction and the effect of designs on the movement of material. Owner representatives also may not fully appreciate material handling issues and are likely to look at whether changes to improve this aspect of construction would pay for themselves and hence be a valuable investment. For example, significant spending for additional square footage that would facilitate material storage and handling during construction but not be revenue-generating space in the finished facility might not pass a cost–benefit test. There is also some evidence that designers were less familiar with ergonomic risks compared to traumatic safety risks like falls or eye injuries. This is confirmed by an Intel LCS review facilitator who commented that it took time and education for him and others to understand that LCS was looking as much at prevention of musculoskeletal injuries from poor ergonomic design as at prevention of eye injuries, lacerations, and falls that are more readily understood as construction risks. Other research supports this finding as well. In their study of a large engineering design firm designing offshore installations for the Norwegian oil industry, Wulff et al. (1999) found that designers did reasonably well with design features directly related to disaster prevention but had poor familiarity and took little action related to human factors for normal operations of the finished facility. On the other hand, design changes related to access and fall protection on the DID project were incorporated to a greater extent, being implemented in 69 and 80% of the cases, respectively. Design suggestions to address access and fall protection issues are perhaps easier to visualize, less costly, easier to implement, or integrate well with the other project goals.

The Relationship between Life Cycle Safety and Identified Design Changes

As noted above, one of the methodological challenges in our assessment of LCS is that many of the documented design changes

Table 6. Importance of Having Life Cycle Safety Review in Addition to Standard Technical Review ($n=24$)^a

	Design change not implemented	Design change implemented
Noted in LCS process (programming or LCS review) only	4	6
Noted in technical review only	0	0
Noted in LCS process (programming or LCS review) and technical reviews	4	9
Not noted in LCS process (programming or LCS review) or technical reviews	1	0

^aDoes not include: Case number 16—center-build, and Case number 18—slow response to requests for information.

Note: LCS=Life cycle safety.

may have occurred without this specific safety-in-design process. In our interviews with Intel, IDC, and Hoffman personnel who participated in the LCS process during programming, some individuals note that they “would have gotten there anyway,” meaning that the design changes would have been noted and implemented through the technical design review process already in place. If this were the case, the LCS process would be redundant and perhaps not worth the considerable investment of time and money.

To determine whether LCS independently led to design changes being raised and considered, the cases were organized according to whether they were noted in the LCS process (during programming or in an LCS detailed design review) and/or the technical design review (see Table 6). In compiling data for this table, we eliminated two cases (numbers 16 and 18) since these changes would not typically be the subject of either a technical or LCS review. If a proposed design change was noted in Intel’s normal technical review process, then it is possible that the technical review process would lead to a design change. If, on the other hand, items were not noted during the technical review and were picked up only in the LCS process, this would be an indirect indication that LCS led to design changes on D1D.

Of the 15 design changes implemented, six were noted only in the LCS process, none were noted in the technical review only, and nine were noted in both the LCS process and the technical reviews. The six implemented design changes noted only in the LCS process—utility level below subfab (Case number 1), subfab ceiling height (Case number 2), welded truss connections (Case number 3), brace connections (Case number 15), utility rack access (Case number 19), and ground pads (Case number 25)—were judged in trade contractor focus groups as being successful design interventions. Since these design changes appear to have originated in processes unique to the LCS process, we may view them as being a direct result of LCS. In other cases where desired design changes were noted in the technical review process and the LCS process, it might well be the case that LCS contributed to the decision to introduce these design changes. Again we must note that several of these cases involved more than just safety impacts. Cases 1–3 all fall into this category and had major impacts on schedule and congestion in the fab and on the site. However, this should not diminish the fact that all were actively discussed in the forum of LCS, which may or may not have occurred in the absence of the LCS process.

Impact of Life Cycle Safety on Construction Worker Safety

The preceding analysis indicates that the LCS program did lead to design changes on D1D, and that there is some evidence that the likelihood of a proposed design change being implemented is a function of the timing of the suggested change, the origin of the suggestion, and the category of the suggestion. A question remains as to whether the implemented changes had their intended effect of reducing risk to construction workers. While there is considerable evidence that the study site was quite safe by industry standards, we must remember that LCS was but one of many safety initiatives at D1D, and it would be incorrect to credit LCS or any one program exclusively for the good safety record. Thus, to assess the safety impact of D1D we rely on two different approaches. First, we examine exit focus interviews from trade contractors to understand the impact of proposed design changes. Second, we use our knowledge of the construction industry to assess whether key design changes on D1D were likely to lead to reduced risk exposure for construction workers.

In exit focus groups, trade contractors provided input related to each case. From this input it could be determined whether they thought the design helped improve safety, whether the safety hazard remained, or whether another problem was created. This input was analyzed both for cases in which proposed design features were implemented and for those where they were not. Based on this analysis, 14 of the 26 design changes were specifically mentioned as improving worksite safety. The two cases in which implemented design changes did not have their intended effect were “clean room floor coating” (Case number 6) and “adequate power supply” (Case number 21). In the former, the new coating used caused the same problem with tackiness as the floor covering used on previous fab construction sites. With regard to inadequate power supply, the remediation steps taken did not satisfy the original concerns of the trade contractors who first noted the problem.

Beyond evidence from the exit focus groups, our assessment of major design changes resulting from LCS indicates reduced construction worksite risks on D1D. The creation of a utility level below the subfab (Case number 1) and raising the ceiling height of the subfab (Case number 2) were two notable design changes resulting, in part, from the LCS process. By providing more space and height for a variety of trade workers, these design changes reduced ergonomic risks, reduced headknocker risks, and likely alleviated problems related to congestion, access, and material handling. These changes may have had the added benefit of increasing labor productivity since trade workers could install plumbing and electrical equipment standing rather than in awkward or constrained postures. Likewise, establishing 42 in. parapet heights (Case number 11), creating a walkable ceiling (Case number 26), and designing in anchorage points for fall protection (Case number 12) reduced risks from falling from heights and may, too, have increased worker productivity. Prefabrication of welded truss connections (Case number 3) also likely reduced risks on D1D, but may have shifted risks to the off-site facility where the trusses were fabricated. While a definitive assessment of the impact of these design changes may never be possible due to the unique design of D1D and the number of confounding variables that can influence safety outcomes, the design changes documented on D1D certainly appear to have had a positive impact on reduction of hazardous exposures. Whether this translated to reduced costs of injuries is not testable with existing

data, but if some of the design changes improved productivity as well, there is a strong argument for a net benefit to the project from LCS.

Conclusions and Recommendations

Safety-in-design processes can take many forms and lead to varied results. The effectiveness of such processes in positively impacting a design depends on many factors associated with the project team members, the scope of the project being designed and built, and the nature of the process itself. The LCS process implemented by Intel on the DID construction project represents one means for addressing safety in the design of a project. The LCS is a comprehensive process that involved many different parties throughout the course of programming, design, and construction.

The study of the LCS process revealed that it was successful in eliminating or mitigating significant safety and health hazards during construction. The LCS surfaced and promoted design changes that otherwise might not have been implemented on DID under the traditional technical design review process only. This success is enhanced through the consideration of design changes early in the project. The process should ideally start in the programming phase and continue through detailed design. Another significant factor was input from trade contractors. Design changes noted by trade contractors were more often implemented in the design and more frequently deemed a success in improving construction worker safety. Their involvement in the process is beneficial not only during programming, but also during detailed design. Finally, the study showed that it may be particularly difficult to address and implement design changes intended to improve material handling during construction and retrofit, while those aimed at providing safe access to the work and fall protection appear to be more readily understood and accomplished.

We recognize that LCS was distinctive both for its scope and the level of organizational commitment that this large owner dedicated to this effort. While replicating an effort as extensive as LCS may not be practical in general commercial construction, developing less comprehensive but nonetheless meaningful safety-in-design initiatives can be practical. Increased awareness, the development and continued refinement of safety-in-design checklists, and structured interaction between designers and builders during which safety implications of specific design features are discussed, can result in safer designs. These processes are likely to be easily introduced within a design-build project delivery model, where designers and constructors work together in one firm. However, programs in the United Kingdom (MacKenzie et al. 2000) and Australia (WorkCover 2001) also illustrate that that design review by engineers with occupational safety and health knowledge can lead to enhanced safety outcomes within more traditional design-bid-build contracting arrangements. In the United States, constructability reviews also provide an opportunity to integrate safety into design, provided that safety is made a priority in such reviews and those involved in the constructability review have sufficient training and expertise in construction site safety.

The British experience with legally mandated designer involvement in construction phase safety illustrates that the challenge is cultural as well as structural (Cosman 2004). Opportunities must be created for designer-constructor interaction in the course of specific projects, but designers must also be convinced of the role they have to play through university and continuing

education and industrywide campaigns. "Action needs to be focused on resolving the discontinuities between the knowledge about design implications, the skills to deliver better designs, and the drivers affecting the scope and conduct of design activities" (Cosman 2004, p. 65).

The complexity of the LCS process, coupled with the large and complex nature of this construction project, presented inherent challenges to the research effort. It was difficult to isolate the impact of the safety-in-design process amidst the other safety processes and programs on the site and other influential project characteristics. Overcoming these challenges might come about by examining a safety-in-design process across multiple sites. Additionally, early involvement of third-party researchers in how design changes are documented and how related project and safety information is collected could facilitate future studies. Narrowing the focus to specific design elements might also make for a cleaner study with clearer outcomes. Our experience suggests that this area of research may be one in which participant observers from the design and construction fields have an important role. The impact of implicit knowledge and informal relationships on design and construction processes suggests the need for an ongoing "inside" and real-time view in order to fully understand the relative importance of different factors in design decisions.

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