

Exploring the relationship between lean design methods and C&D waste reduction: three case studies of hospital projects in California

Explorando la relación entre los métodos de diseño lean y la reducción de residuos de construcción y demolición: tres estudios de caso de proyectos hospitalarios en California

Burcu Salgin ^{1*}, Paz Arroyo **, Glenn Ballard ***

* Erciyes University, Kayseri. TURKEY

** Pontificia Universidad Católica de Chile, Santiago. CHILE

*** University of California, Berkeley. USA

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Abstract

The lean ideal is to deliver customer value without waste. Traditional sustainability outcomes, which are attributed to the pursuit of the lean ideal in construction projects, consisted of economic outcomes instead of environmental outcomes. This paper explores how lean design methods can reduce construction and demolition (C&D) waste and contribute to environmental sustainability. Three case studies are conducted to analyze three hospital projects in California that employed lean tools and methods during design. These three cases demonstrate that C&D waste reduction (e.g., recycling construction waste, reducing material use, and enhancing recovery after use) can be indirectly achieved by economic waste reduction. Testable hypotheses were generated from the case study findings and were proposed as future research topics.

Keywords: Lean design, construction and demolition waste, solid waste reduction

Resumen

El ideal del concepto Lean es entregar valor al cliente sin desperdiciar nada. Los resultados sustentables tradicionales, que persiguen el ideal Lean en los proyectos constructivos, son más bien resultados económicos en vez de resultados ambientales. Este artículo estudia cómo los métodos de diseño eficientes pueden reducir el volumen de residuos de construcción y demolición y contribuir a la sustentabilidad del medio ambiente. Se realizaron tres estudios de caso a fin de analizar tres proyectos hospitalarios en California que emplearon herramientas y métodos Lean durante la fase de diseño. Estos tres casos demostraron que la reducción de residuos de construcción y demolición (por ej., reciclar desperdicios de la construcción, reducir el uso de materiales y promover la recuperación después del uso) se puede lograr indirectamente a través de la reducción del desperdicio económico. Se generaron hipótesis comprobables a partir de los hallazgos de los estudios de caso, las que se propusieron como temas para futuras investigaciones.

Palabras clave: Diseño Lean, residuos de construcción y demolición, reducción de desperdicios

1. Introduction

The construction industry exerts a significant impact on the environment, such as noxious gases released into the atmosphere, the extensive use of water, and the generation of construction and demolition (C&D) waste. C&D waste generated by construction is defined by the Scottish Environmental Protection Agency (2014) as "...materials resulting from the construction, remodeling, repair or demolition of buildings, bridges, pavements and other structures and the use of energy, materials and labor which does not add value to the construction process."

C&D waste is considered to be a major problem in the construction industries of developed countries and is becoming an increasing problem elsewhere. Building construction, renovation, use and demolition constitute approximately two-thirds of all nonindustrial solid waste generation in the US EPA (US EPA 2003).

Compared with household waste, the safe disposal of C&D waste is difficult because it may contain hazardous materials, such as asbestos, heavy metals, persistent organic compounds and VOCs (Esin and Coşgun, 2006; Arslan et al., 2012). C&D waste threatens human health and the natural environments.

Currently, many countries experience increasing C&D waste volumes and diminishing landfill capacities. In developing countries, 500-1000 kg/inhabitant/year of C&D waste is generated (Kartam et al., 2004); this amount constitutes 10-30% of the landfill areas in the world (Begum et al., 2006).

To reduce C&D waste, various waste management models have been developed. These models involve prevention, reduction, reuse, recycling, landfill and disposal. Preventing and reducing waste are the most effective strategies. These strategies can be applied to the construction industry, especially during the design phases of projects. In this paper, it is also discussed C&D waste from the perspective of prevention.

¹ Corresponding author:

Assistant. Professor, Dept. of Architecture, Erciyes University, Kayseri, Turkey
E-mail: bsalgin@gmail.com



The lean ideal is to provide a custom product that achieves a specific purpose, can be instantly delivered without waste, and eliminates all types of waste (environmental, social and economic) throughout the process. This ideal is pursued via the application of principles and methods, including lean design methods. This study introduces the main lean design methods and seeks direct and indirect relationships between these methods and C&D waste prevention/reduction. Three case studies of hospital projects in California are analyzed, which applied lean design methods in the design and construction process to understand how these methods can reduce C&D waste.

2. Research question and methods

It is proposed to answer the following research questions in this paper: 1) Do lean design methods reduce C&D waste? and 2) How do lean design methods reduce C&D waste? To answer these questions, it has been reviewed the literature regarding lean design, and C&D waste reduction, and conducted three case studies of complex hospital projects.

In the literature, studies have been identified about lean practice and its connection to economic benefits (e.g., Ballard, 2000, 2009; Ballard et al., 2008; Howell and Ballard, 1994) and studies that discussed how construction can be more sustainable with lean principles. It was only found one study that identified a clear connection between lean practice and C&D waste reduction (Agyekum et al., 2013). Agyekum et al. (2013) explores this connection during the construction phase, whereas our focus is the benefits of applying lean methods during the design phase. The relationship between lean design methods and C&D waste reduction was not identified in the literature review. Numerous studies have focused on ways to improve onsite waste management and recycling activities; however, no study has attempted to address the effect of design methods on waste generation.

To understand the impact of lean design methods, it was needed to evaluate real projects that apply these methods. For this reason, case study methodology based on qualitative methods is employed in this research. Qualitative methods investigate the why and how of the research problem and are not limited to the what, where, or when. Thus, smaller but focused samples are more frequently required compared with large samples (Flyvbjerg, 2011). Therefore, the analysis based on three detailed case studies, which were developed based on the guidelines by Yin (1994). In this study, it is attempted to understand how and why lean design may contribute to C&D waste reduction. It is not testing a hypothesis. Testable hypotheses are expected to emerge from this phase of the study.

Three hospital projects in California were selected due to their technical and organizational complexity, involvement by multiple specialists and stakeholders, and implementation of multiple lean design methods. The selected projects are: Sutter Medical Center Castro Valley (completed), Temecula Valley Hospital (completed), and Van Ness and Geary Campus (under construction).

The first two projects were completed prior to 2014. The third project—the Van Ness and Geary Campus—was in the early stages of construction at the end of 2014 but offers valuable information about the impact of lean design methods on C&D waste.

The hospital projects, which consist of greenfield projects (not renovations or additions to existing facilities) in California, employed lean design methods. The first project is located in a suburb of San Francisco, the second project is located in a rural area in Southern California, and the third project is located in downtown San Francisco. All projects must comply with California legislation that requires that every acute care hospital be immediately operable after a major earthquake, according to the State of California, Office of Statewide Health Planning and Development (OSHPD). Therefore, the design of the projects had to be coordinated with OSHPD reviewers.

Table 1. Data collection from case studies

#	Data Collection Method	Project Name	Employer	Position
1	E-mail	Sutter Medical Center Castro Valley	DPR Construction	Project Manager
2	E-mail	Sutter Medical Center Castro Valley	DPR Construction	Project Manager
3	E-mail	Temecula Valley Hospital	DPR Construction	Project Superintendent
4	Interview	Van Ness and Geary Campus	HerreroBoldt Partnership	Senior Project Manager
5	Interview	Van Ness and Geary Campus	HerreroBoldt Partnership	Sustainable Design Coordinator
6	E-mail	Van Ness and Geary Campus	SmithGroup JJR	Principal

Data were collected via interviews and document analysis. Table 1 lists the various professionals (architects, contractors and owners) that were interviewed. Data from reports, design documents, and published research papers on these projects were collected and analyzed. For the construction projects, the authors connected with the engineers and architects via e-mail. For the Van Ness and Geary Campus project, the researchers conducted numerous personal interviews. The objective of the interviews and document analysis was to understand 1) the lean methods used to design the hospital and 2) how lean design methods reduce C&D waste. Open-ended interview questions were preferred to ensure that participant responses were not limited or guided. The interview questions are as follows: What lean tools did the designers use during the design stage? The lean approach aims to reduce all types of waste. Was C&D waste reduction a priority during the design stage? Can you mention examples of C&D waste reduction? Do you think these reductions were related to lean design methods?

3. Ways to reduce C&D waste

It is identified the following ways to reduce C&D waste as the most relevant methods for this research objectives:

- reduce the required amount of materials, e.g., reduce the size of a building that provides the same service
- select materials to reduce their negative impact on the environment, e.g., select building materials that are easy to recycle
- reduce the amount of wasted materials; i.e., scrap, the difference between the total amount of purchased materials and the total amount of consumed materials
- increase the useful life of buildings, e.g., design the building for flexibility and retrofitability, which reduces the amount of C&D waste that is generated over time.

Other means that are less impacted by product and process design decisions, e.g., recycling scrap materials, exist. a), b) and d) are clearly impacted by the design of a building, whereas c) reducing the amount of wasted materials can be achieved by various approaches, such as (1) prefabrication and preassembly in shop conditions, (2) prevention of dimensional clashes, and (3) improvements in construction quality, which results in reduced rework. The first two approaches pertain to the technology instead of the design management, whereas the third approach seems to be dependent on distinct and effective processes for shop fabrication and site assembly, i.e., process design that is distinct from product design. We return to this distinction between the objects of design in our recommendations for future studies.

4. Lean design methods

Lean design methods derive from lean thinking, in which value and waste are core concepts. Value is defined as follows: Value enables realization of purpose. Value is a property that is not inherent in an object; it is relative to a customer's objectives. According to Ohno (1988), seven types of waste exist: defects, delays (due to waiting for the completion of upstream activities before another job can

begin), overprocessing (producing products with characteristics that are not valued by their users), and overproduction (beyond what is required, maintaining excess inventory, unnecessary transport of materials and unnecessary movement of people). It is proposed the following definition: Waste is anything with a cost of any kind, the elimination of which does not reduce the delivered value.

Lean thinking is a philosophy that is based on the lean ideal and the principles followed in the pursuit of that ideal. Application of the principles may involve tools or methods that originated outside the lean community and are appropriately adapted. Many of the lean methods from manufacturing have been applied to the construction phases of projects (Howell and Ballard, 1994; Huovila and Koskela, 1998), e.g., empowering direct workers to 'stop the line' rather than allowing defective products to proceed beyond their work station. However, few studies discuss lean design methods in construction projects. In this study, it is identified nine lean design methods that encompass an extensive range of functions; e.g., steering design, targets, planning and control, and decision-making and documentation. These methods are described in the following section.

(1) Integrated project delivery (IPD) is a specific instance of the lean project delivery system; it is based on a multiparty contract that is signed by all key members of the project team (architect, key technical consultants, general contractor and key specialty contractors), including the owner. IPD enhances collaboration and transparency throughout the design process and enables an entire building perspective and accounting for interactions among building systems, which is important in building design. According to Howell and Lichtig (2010), lean practice and IPD add "A production management view into how the work of design and construction actually gets done". Moreover, IPD and lean require the team to openly engage in an explicit effort to align the operating system with a collaborative organizational structure and commercial terms that support project-wide optimization through the use of relational contracts.

(2) Target value design (TVD) is a collaborative method in which stakeholders are introduced early in the design process. With the design team, they define the objectives and conditions of satisfaction that will drive the design of the building. Unlike the traditional process, in which a design is produced and financed in TVD, the design is steered within the client's allowable cost and time.

(3) Set-based design (SBD) is a method in which designers collaboratively explore alternatives and keep them open until the last responsible moment to reduce negative design iteration (Ballard, 2000). This method contrasts with point-based design, in which one alternative is selected early in the design process (for example, a floor to ceiling/floor to floor height) and is subsequently proven to be infeasible by someone downstream in the design process (for example, a mechanical engineer/contractor cannot fit their duct work within the interstitial space). This disadvantage results in late changes in the design process, which requires reworking by various specialists. Because less time is wasted in negative iterations (rework), more time is available to explore and develop alternatives that are more complex to implement and require more collaboration.



(4) **Choosing by advantages (CBA)** is a method of selecting from alternatives when multiple factors are relevant to evaluating and differentiating the alternatives. CBA is also well aligned with lean thinking (Arroyo et al., 2012). CBA is a decision-making method that complements the dynamic set-based design methodology throughout its different stages (Parrish, 2007) (Thanopoulos, 2012). This collaborative decision-making method helps the project team to explore more alternatives and identify advantages between the alternatives.

(5) **A3 reports (A3)** are formats for presenting proposals or status reports that are generated via a process of consensus building, which prompts a thorough understanding of the current situation (the facts) and systematic experimentation and learning.

(6) **The Last Planner System (LPS)** was developed by Glenn Ballard and Greg Howell is a production planning system that is designed to produce predictable work flow and rapid learning in the programming, design, construction and commissioning of projects (Ballard 2000).

(7) **Value stream mapping (VSM)** is a lean tool that is extensively used to identify waste and opportunities for process improvement. According to Rother and Shook (2003), "VSM it is used by Toyota Production System practitioners to depict current and future, or "ideal" states in the process of developing implementation plans to install Lean systems... A Value Stream is all the actions currently required to bring a product though the main flows essential to every product.

(8) **First run studies (FRS)** comprise a tool to design repetitive processes to satisfy criteria (e.g., criteria for safety, quality, time

and cost) and test the designs in the 'first run', which comprises the first execution of the process. "Collaboratively" indicates that the design and testing are performed with the persons who responsible for executing the processes. Nonrepetitive processes are designed and tested using virtual and physical prototyping.

(9) **Building information modeling (BIM)** is a tool that can support lean thinking by providing a platform to verify the design and its value for the customer. BIM enables coordination between specialties and the evaluation of construction strategies during design.

From this list of methods, organizational structure, commercial terms, and management methods are intended to have a systemic effect on attitudes, culture, and performance. Consequently, their impact on outcomes, such as C&D waste reduction, is infrequently limited to the use of a single method but is the combined impact of the lean philosophy. The purpose of these tools is not limited to the reduction of C&D waste but also include the optimization of the design and the indirect reduction of C&D waste, as shown in the following case studies.

5. Case studies

This section presents three hospital projects that employed the nine lean design methods described in the previous section during their design phase. The characteristics of the three northern California hospital projects are summarized in Table 2.

Note that these completed projects have been very successful in terms of owner satisfaction and achievement of purpose, as well as budget and time completion (Table 3).

Table 2. Characteristics of the case studies

Characteristics	Sutter Medical Center Castro Valley (completed)	Temecula Valley Hospital (completed)	Van Ness and Geary Campus (under construction)
Beds	130 beds	140 beds	274 beds (304-bed extension)
Square feet	230,000 sf	177,506 sf	740,000 sf
Cost	\$320 million	\$151 million	\$1 billion
Construction duration	36.3 months	30 months	48 months

Table 3. Case studies

Project Results	Sutter Medical Center Castro Valley	Temecula Valley Hospital	Van Ness and Geary Campus
On time	Yes, the project was completed six months early (Conwell 2012)	Yes	Under construction
Within budget	Yes	Yes, the project was completed 40% below market cost, i.e., the cost per acute care hospital bed in California	Under construction
Certifications achieved	LEED Silver	No certification	LEED Silver

In the next section, it is described each of the three case studies, including details about the employed lean design methods and the evidence of C&D waste reduction.

5.1 Sutter Medical Center Castro Valley

5.1.1 Background

This hospital project is located in Castro Valley, California. According to the general contractor DPR Construction (2014a), this project was the first project in the industry to employ an 11-party IPD contract, in which the owner and ten participants are contractually required to collaborate. They used an Integrated Form of Agreement (IFOA) contract (DPR Construction, 2014a). In previous cases, only the owner, architect and general contractor had signed the agreement and formed the core IPD team. The novelty of this contract is that 11 companies comprised the risk pool for the first time and shared gains and risks.

The results for the lean design methods in this project are as follows (Conwell, 2012):

- The project was completed six months early and within budget, which enabled the 11 design and construction firms that signed the multi-party agreement with Sutter Health to achieve near-maximum profits. These profits were above average for similar projects, with less

downside risk (Sutter Health bore the risk of cost overruns that exceeded the profit pool).

- The trade productivity improved between 10 and 20% compared with baselines, depending on trade.
- The labor utilization during construction averaged 70%, which indicated that 70% of paid labor comprised direct production compared with waiting and searching for tools or materials or information.

5.1.2 Evidence of C&D waste reduction

From the literature and interviews (Table 1), it has been discovered evidence of increased recycling and prevention of dimensional clashes. According to two project managers from DPR construction, this result was possible due to project team collaboration and coordination with other partners.

Increased recycling. According to Ferma Corporation—the agency responsible for waste management duties in the project—the project team achieved a very high recycling rate in April 2010 during the construction phase. The amount of green waste recycling comprised 100% and 91% recycling of mixed construction and debris recycling was achieved. Table 4 shows the recycling rates for the incoming tons of waste material from the construction site to Ferma Corporation.

Table 4. Recycling rates during construction phase in 2010

Incoming Products	Recycling Rates	Incoming Tons	Recycled Tons
Green waste	100%	103.39	103.39
Mixed Construction and Debris	91%	109.77	99.89

At the end of the construction phase, the project gained two LEED points from the “Material and Resources/MRc2 construction waste management” category (LEED for NC, 2009). A minimum rate of 75% is necessary to obtain two points and achieve 78% recycled content (DPR Waste Management Report).

Recycling occurs in the construction phase of a project and is minimally influenced by decisions that are made during the design phase. However, it contributes to C&D waste reduction and is included in the case study report.

Reduce the amount of wasted material: Preventing dimensional clashes. The project used BIM to its highest potential. Cross-functional teams periodically reviewed 3D models to obtain better solutions. Design issues were identified and previously corrected via fully integrated BIM models. BIM increased the precision of the design information, which enabled it to be directly employed for fabrication and pre-assembly. Gains in reduced changes and scheduling delays were perceived (Khemplani, 2009). BIM enabled detailed planning, improved logistics, and model-based estimation to generate rapid estimates and provide frequent team access to real-time cost information.

The project’s collaborative design and modeling process resulted in the ability to directly build from the model and yielded cost and time savings via an increased degree of prefabrication of components. According to Conwell (2012), the project achieved breakthrough results in “building to the model”, e.g., the match between an as-built plan and a model for MEP was 97%. The as-built plan was measured by laser scanning, which produced point clouds that were converted into a model and were compared with the design model. Building that close to the model indicates that dimensional clashes were detected and prevented in the design phase, which reduces rework and C&D waste from loss of material during the construction phase.

During the analysis, the team detected that the fixtures in the BIM model were not accurately dimensioned. This detection and modification occurred before the design was submitted to the OSHPD, which prevented wasted time and resources during design and/or construction (Alarcon et al., 2011). Eastman et al. (2011) provides a detailed description of this case study and the use of BIM collaboratively under IPD. The researchers suggest that this result indicates the potential of BIM and the early involvement of stakeholders, which is supported by IPD project delivery.



5.2 Temecula Valley Hospital

5.2.1 Background

This hospital is in Temecula, which is located north of San Diego and south of Los Angeles within the County of Riverside. The owner is Universal Health Services, Inc., which is one of the largest hospital management companies in the U.S.

The owner was very confident about the success of this project, as stated in an interview prior to construction, "This method (referring to lean design methods) allows the owner, architect, and contractor to participate in the design and decision-making process, focusing on the present and future healthcare needs of the South Riverside County community. This collaboration resulted in an accelerated construction timeline and reduced costs. Certain project components were prefabricated offsite to minimize labor and installation time, and trades shared tasks such as hoisting, cleaning, material handling and layout. DPR and Turner Construction Company are leaders in using this emerging lean construction method." (Miller 2011).

5.2.2 Evidence of C&D waste reduction

From the literature and interviews (Table 1), evidence discovered that the required amount of material was reduced and the construction quality was improved. According to the interviews, the collaborative setting achieved by lean design methods enabled the team to develop more innovative alternatives.

Reduce the amount of required material. The design team offered an alternative 'hotel' framing solution that enabled a reduction in floor-to-floor height of 1.3 feet. They saved not only money but also materials (Laski et al., 2014). This approach contributed to C&D waste reduction.

It is considered that this result was possible because the design team was able to enhance innovation, which is

clearly supported by the use of lean methods, such as IPD, which aligns stakeholder commercial interests; TVD, which helps designers to provide value design for the client; SBD, which helps designers to consider a set of alternatives and defend an inadequate design; CBA, which increases the transparency of decision-making; and A3 reports, which help to communicate and document the decisions that enable continuous learning. The combination of these lean design methods enable the design team to implement alternatives that are not distinct or that may be impossible to consider in a more traditional setting.

Reduce the amount of wasted materials: Improving construction quality. The design and construction team used value stream mapping to describe the work flow (Figure 1). They aimed to save time during construction. With this approach, the team reduced not only time but also C&D waste. The value stream map, which was used as a work flow chart for managing the project, gave workers and supervisors the confidence that they were coordinated with all related parties at each stage of the job. Because the sequence of work flow and the release of work between specialists was clearly identified, critical materials were only moved when they were needed in the final product. This approach provided less opportunity for damage on the construction site (Laski et al., 2014). Figure 1 presents an example of the VSM used in this project for the delivery and installation of doors.

The researchers suggest that this result was possible due to the direct implementation of VSM, which enables the design team to design the process and the product. In addition, the collaboration of the contractors and the specialties early in the design enable a more detailed product and process design. In this case, process mapping or VSM not only prevents material damage but also reduces rework and increases productivity.

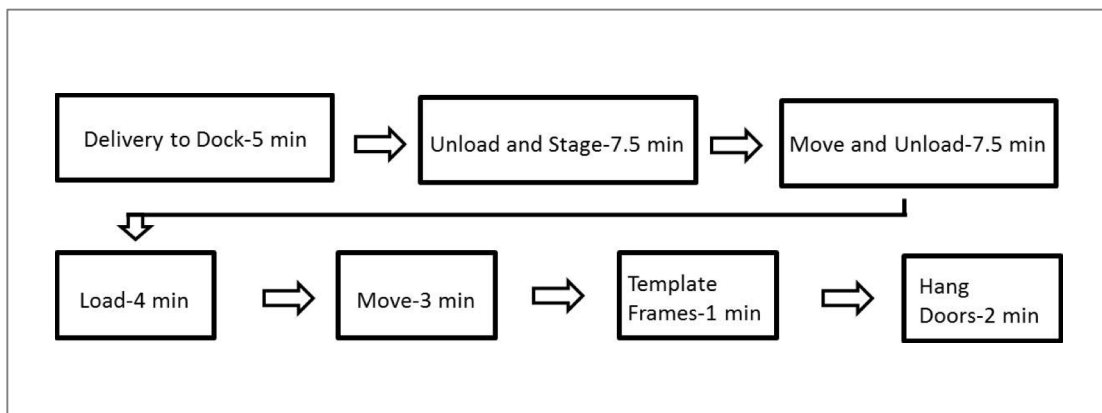


Figure 1. Value Stream Map: Door Delivery and Installation (adapted from Laski et al., 2014)

5.3 Van Ness and Geary Campus

5.3.1 Background

This project is located in San Francisco, California. Formerly known as Cathedral Hill Hospital (CHH), it was originally a 1.2 million square foot (555 beds) urban replacement hospital in San Francisco. In 2014, it was downsized to 740,000 square feet (274 beds) and renamed the Van Ness and Geary Campus (SmithGroupJJR, 2012). The Van Ness and Geary Campus is intended to enable consolidation of critical services in a single location, with ancillary services provided in the remaining three San Francisco campuses.

Working with Sutter Health and HerreroBoldt as the general contractor, SmithGroup Architects designed this large and complex hospital using lean design methods. The new hospital is organized around comprehensive centers of care rather than traditional departments, which enhances the delivery of patient care while improving space efficiencies, workflow and productivity (SmithGroupJJR, 2012).

Applying lean design methods, the design team used a progressive project delivery approach that is referred to as IPD, in which the client, architects, engineers, construction manager, and specialty contractors are collocated (SmithGroupJJR, 2012). The project is being designed to satisfy a LEED Silver rating, which would make it one of the largest hospital projects to seek LEED certification. Unlike the previous two cases, this project deliberately pursued environmental sustainability objectives, including C&D waste reduction.

5.3.2 Evidence of C&D waste reduction

From the literature and interviews (Table 1), it is discovered that evidence of reduce the required amount of materials, select materials that reduce their negative impact on the environment, and increase the useful life of buildings. Because construction on the Van Ness and Geary Campus project commenced during 2014, it can be only provided an explanation for potential savings during construction. In the interviews, it is realized that even when the design team agreed that they were primarily focused on conserving money and time, the methodical pursuit of the lean ideal evidently reduced other waste, including C&D waste. The examples are presented in which the application of lean design methods is expected to result in C&D waste reduction.

Reduce the required amount of materials. In this category, the following four examples of C&D waste reduction were found.

The first example of a reduction in materials is related to the design decision regarding slab-to-slab height. The design team aimed to minimize the slab-to-slab (floor) height to save money and time. Given the collaborative approach employed in the project for all relevant specialties, they were able to innovate and improve the design. In traditional hospitals, the slab-to-slab height is typically 4,6-4,9 meters; however, at CHH, it is less than 4,3 meters. This approach not only saves money and time but also saves materials and resources. As a result, it has an indirect effect on C&D waste prevention/reduction (Lostuvali, 2012).

The second example is related to innovation in structural design. The structural design team used lean design methods to develop an earthquake-resistant building. They established a Virtual First Run Study framework, in which computer

modeling was used to prototype and test a process design (Nguyen et al., 2009) and different alternatives for the structure. One of the applications involved the selection of the installation of the viscous damping wall (VDW). The VDW presented a coordination challenge for logistics and field operations; thus, the team wanted to explore different methods for their installation. The installation of VDWs required the coordination of the structural engineers, the VDW fabricator, the shipping company, the hoisting subcontractor, and the steel structure supplier.

VWDs are a Japanese seismic invention that was not previously employed in the United States. As the structural design evolved, the structural engineer validated the prediction that the VWDs would produce a very efficient structural system with superior seismic performance compared with conventional seismic systems (Ballard et al., 2008). This seismic device reduced the weight of the building due to its working principles. If they had designed the structural system using traditional methods, the total weight of the building would have been 30 lbs/sf. With VWDs, the total weight of the building is 20 lbs/sf., which yields a net reduction in steel tonnage in the range of 4000-7000 tons (Lostuvali, 2012). It saves money and time, as well as materials and resources.

The third example is the reduction of the total space required to maximize value and the quality of care for patients in hospital buildings. Institutional facility changes must be coupled with organizational priority setting and planning for greater efficiency. The design team applied lean principles to develop plans for the hospital that break down traditional departmental boundaries—both functional and physical—in favor of an integrated services platform (Hannon, 2010).

The program aimed to enhance patient care and improve workflow and productivity throughout the system by integrating departments around each point of service. These improvements also eliminated excess capacity and support spaces, which reduced the total amount of required space (Hannon, 2010). The approach promotes “do more with less”. This approach on the designing level enables the creation of more efficient spaces with fewer materials. As a result, a positive effect on C&D waste reduction is expected.

The fourth example concerns acoustical material selection. Typically, hospitals are noisy places. HerreroBoldt Partners collaborated with the acoustical consultants Shen Milsom and Wilke (SM&W), framing trade partner KHS&S, SmithGroup Architects, and Serious Materials to design the most cost-effective hospital that satisfied the noise requirements of the project.

The project has three classes of walls; each satisfy different acoustic requirements: sound transmission class (STC) 40, 45 and 50. A higher STC indicates a better attenuation of airborne sound by the wall partition. The originally designed STC 45 wall for the CHH had three layers of regular gypsum sheetrock. The STC 50 wall was designed using four layers of regular gypsum sheetrock. However, because the acoustical consultant wanted a more conservative design, the acoustical consultant selected QuietRock ES. To compare the performance between the three layers of regular gypsum and one layer of QuietRock ES and between four layers of regular gypsum and two layers of QuietRock ES, the two designs were tested. In this



comparison, the one-layer and two-layer QuietRock ES designs performed as well or better than multilayer gypsum assemblies with cost benefits. Together, HerreroBoldt, SM&W, KHS&S, and SmithGroup decided to use QuietRock ES based the advantages (QuietRock Case Study, 2006). This decision achieved the following results: Reduction of 101,339 SF of gypsum wall board delivered to the job site due to replace double layers of gypsum. Reduction of drywall screw inspections due to one layer of gypsum. Six fewer 30 yd dumpsters to remove gypsum scrap. Finally, increase the livable space in the building by 1,300 square feet by replacing the multilayered gypsum walls with QuietRock ES.

The researchers propose that this result was possible because the design team was able to enhance innovation during the design. As previously mentioned, the alignment of the stakeholders' interests was supported in this project by IPD.

In addition, the design team was able to innovate and make decisions that were collaboratively supported by the use of TVD, SBD, CBA, and A3. When using TVD, the design team defines the alignment, establishes targets, and the project is proactively steered toward them. The needs and requirements define the set of design alternatives (design space) within which a selection must be made. Preferences are used to select from alternatives within the design space. The design team identifies acceptable, although not optimal, alternatives to prevent rash decision-making. This strategy, which is based on SBD, provides more time to explore additional alternatives and collaborative decision-making using CBA. CBA helps the design team to differentiate alternatives by considering multiple factors. Decisions are documented as a problem solved in an A3 report, which includes a CBA analysis that proposes that a specific alternative be selected. This practice prevents iterations or changes in the decisions because relevant stakeholders were involved in the decision-making process and the rationale for the decisions are made by consensus. The researchers suggest that this lean design method supports innovation, which results in better projects, including C&D waste reduction.

Although many of these design solutions may not include lean methods, it is believed that the use of lean design methods facilitated the design process. In addition, the use of the last planner system in this case study increased the workflow reliability and provided time during the design phase for reflection and creativity.

Selecting materials that reduce their negative impact on the environment. This example is related to designing for decommissioning. The design team selected materials that can be disassembled instead of materials bound together by adhesives. As a result, this approach has a direct effect on C&D waste prevention/reduction (Brunel, 2012) and enables recyclability of building materials. The selection of materials is an important part of the design. In this case, the design team had a conscious intention of reducing C&D waste after the end of the project life cycle. The researchers suggest that lean design methods supported the innovation and selection of materials using SBD and CBA.

Increase the useful life of buildings. CHH's life expectancy is 40 years. The design team agreed that the hospital will not be completely demolished at the end of its life cycle due to its unique and flexible design. For example, the design team selected materials that are easy to replace or upgrade. As a

result, this approach has a direct effect on C&D waste prevention/reduction (Lostuvali, 2012) (Brunel, 2012) and enables conversion to alternative uses rather than demolition.

The researchers identify a connection between lean design methods and the result. Due to the alignment of the stakeholders in this case, the design team was able to design for the best value for the owner based on their future needs instead of the fastest or most inexpensive building design method.

6. Discussion

These case studies of lean design methods provided the following examples of C&D waste reduction:

- When design teams did not directly reduce C&D waste, they implemented innovative methods during the design phase to reduce cost and time reductions that resulted in indirect C&D waste reductions.
- Collaboration was the key to obtaining the coordination and innovation to modify typical design techniques that are employed in hospital projects. The use of lean design methods was crucial to enable innovation and interactions among the designers at the Castro Valley, Temecula Valley, and Van Ness and Geary campuses. Hospital projects are complex; therefore, a significant potential for making mistakes during the design stage exists. These types of projects require a high level of coordination and communication to prevent mistakes. According to Osmani et al. (2008), poor coordination and communication among parties during the design stage (delayed information, last minute client requirements, slow drawing revision and distribution) causes C&D waste during construction. Therefore, it is proposed that lean design methods improve coordination and collaboration, which helps to reduce C&D waste during construction.
- The use of lean design methods such as (1) IPD, (2) TVD, (3) SBD, (4) CBA, (5) A3, (6) LPS, (7) VSM, (8) FRS, and (9) BIM helped the design team to innovate and develop solutions that reduced cost, the schedule and C&D waste.

Using these case studies, it is not able to provide a direct causal relationship between lean design methods and C&D waste reduction. However, testable hypothesis are proposed. The authors have developed the following hypotheses:

1. Cost and time reductions via lean design methods results in C&D waste reduction. If the designers adopt a conscious approach to the prevention/reduction of C&D waste when using lean design methods, additional C&D waste reductions can be achieved.
2. Innovation is enhanced and supported by IPD, TVD, SBD, CBA, and A3, which enables the design team to implement new ideas. These ideas enable the design team to improve in all areas and indirectly reduce material quantities and C&D waste.
3. A systematized method for making decisions using SBD, in which many options are collaboratively analyzed, and CBA, in which decisions are made transparently by

consensus, enables the design team to achieve better results regarding C&D waste reduction.

4. A systematized method of planning and controlling using the Last Planner System® increases the workflow reliability and provides more time for thinking, design and planning the work by detecting initial errors and reducing rework. Detecting errors during the design phase reduces errors during construction C&D waste from rework or mistakes.
5. An applied continuous improvement philosophy using VSM enables the design team to systematically evaluate what can be improved, which also impacts C&D waste reduction by reducing rework and increasing productivity.
6. New ideas are tested using FRS, which enables more accurate results and improved confidence in applying new materials or systems that may reduce C&D waste.
7. BIM used in an IPD setting provides better detailing during the design phase. Detailing errors were identified as a significant origin of waste during the design process. Therefore, better detailing also results in C&D waste reduction.
8. Prefabrication was commonly used in the three cases, which was supported by the high level of collaboration achieved through the implementation of lean design methods. The literature indicates that prefabrication of components contribute C&D waste reduction because standard dimensions and prefabricated units help to prevent onsite cutting of material cutting. Dainty and Brooke (2004) reported that the use of offsite prefabrication causes better control of waste and damage. It is suggested that lean design methods support prefabrication by improving the confidence of the design team regarding product and process design, which facilitates C&D waste reduction.

7. Conclusions

This paper provides an understanding of how lean design methods can reduce C&D waste and presents the first step in understanding the potential benefits of lean design methods in reducing C&D waste. Our case study introduced lean design methods and presented examples of their indirect impact on C&D waste reduction.

The cases provided evidence of C&D waste reduction as result of lean design methods:

- Reduce the amount of required materials. In Temecula and the Van Ness and Geary campus the design team reduced the floor heights. On the Van Ness and Geary campus, the design team reduced the steel weight of the building, the total building size relative to the intended use, and the partition wall material, which caused material reduction. These results were the consequences of design decisions rendered to deliver customer value within their conditions of satisfaction, which is the appropriate focus for waste reduction of all types because waste is relative to customer value; however,

this argument requires more careful and complete consideration.

- Select materials to reduce their negative impact on the environment. On the Van Ness and Geary Campus, the design team selected materials that are easy to recycle.
- Reduce the amount of wasted materials. In Castro Valley, the design team achieved a high level of clash detection in the BIM model during design, which prevented errors and rework. In Temecula Valley, the design team improved the construction quality and prevented material damage due to detailed planning during construction.
- Increase the useful life of buildings. On the Van Ness and Geary Campus, the design team selected materials that were easy to replace and upgrade to extend the life cycle of the hospital.

It is also discovered evidence of increased recycling rates during construction; however, additional research is needed to understand the contribution of lean design methods.

This study provides evidence of various types of C&D waste reduction that were supported by lean design methods. However, a direct causal relationship was not demonstrated between lean design methods and C&D waste reduction in this study. Therefore, it is recommended additional studies to extend this research and thoroughly test the identified hypotheses. These hypotheses are statistically demonstrated by comparing the results of projects using lean design methods versus projects that do not use them. However, this study provides evidence from three case studies using lean design methods and an explanation of how these tools may support the reduction of C&D waste.

The authors believe that cost and time reductions may indirectly cause C&D waste reduction. However, C&D waste reduction using lean design methods may further improve the results. From a more philosophical tangent, the interdependency of different types of waste (e.g., economic, social, and environmental waste), the relationship between lean design tools and environmental waste, and the interaction between product design and process design needs to be better understood.

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