POSITIVE VS NEGATIVE ITERATION IN DESIGN

Glenn Ballard[1]

ABSTRACT

Iteration is essential for generating value in design processes. However, not all iteration generates value. Iteration that can be eliminated without value loss is waste. Moving towards lean design requires a better understanding of both value generation and waste reduction. This paper contributes to the development of lean design by examining how waste can be reduced through elimination of negative iteration. Preliminary research findings are presented regarding such design management techniques as reduced batch sizing and set-based design. Future research is proposed.

KEY WORDS

Iteration, lean design, set-based design, value, value generation, value loss, waste

[1] Research Director, Lean Construction Institute, 4536 Fieldbrook Road, Oakland, CA 94619, 888/771-9207, FAX 510/530-2048, ballard@ce.berkeley.edu; Lecturer, Civil and Envir. Engrg. Department, 215-A McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712

INTRODUCTION

DESIGNING VS MAKING

Within the lean construction community, production is understood as an integrated process of designing and making artifacts. However, designing and making are very different (Table 1). First, designing of product and/or process can be likened to producing a recipe, which is then used to prepare the meal. This is the ancient distinction between thinking and acting, planning and doing. One operates in the world of thought; the other in the material world.

Table 1: Designing versus Making

DESIGNING	MAKING
Produces the recipe	Prepares the meal
Quality is realization of purpose	Quality is conformance to requirements
Variability of outcomes is desirable	Variability of outcomes is not desirable
Iteration can generate value	Iteration generates waste

Second, they differ in the concept of quality appropriate to each. One the one hand, a design, in part or whole, is judged ultimately against its fitness for use (Juran & Gryna, 1986); i.e., the extent to which it realizes the purposes of those for whom the artifact is being produced. On the other hand, the artifact itself, in part or whole, is judged by its conformance to the geometry and specifications expressed in the design, on the assumption that the design has previously passed its own quality hurdles. This suggests the importance of avoiding value loss at the handoffs in the chain from values and needs to design criteria to the design itself and finally to the constructed artifact (Figure 1).

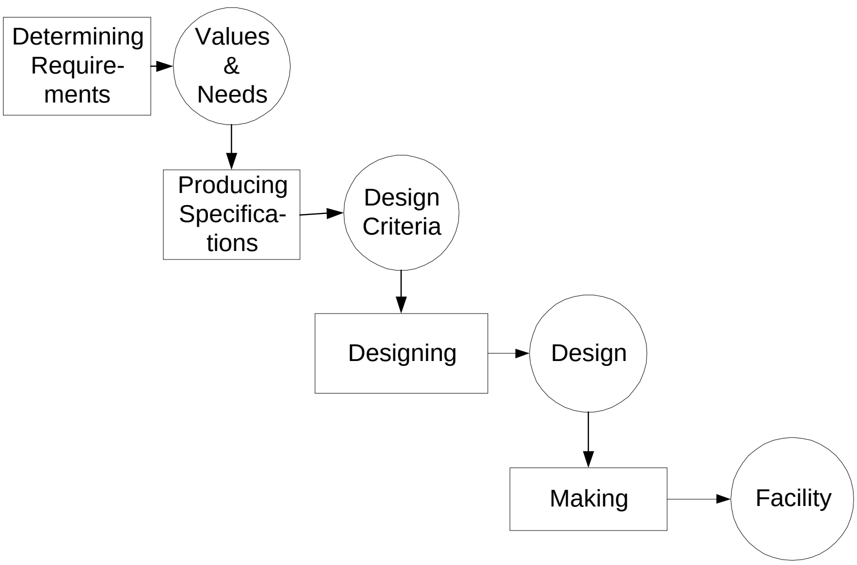


Figure 1: Handoff Control

Third, variability of outcomes has opposite valuations. In making, variability of outcomes is not desirable[2]. This follows quite closely from the concept of quality as conformance to requirements. Requirements are established, then something is made and evaluated for conformance[3]. By contrast, if design products were perfectly predictable, the design process would not be adding value. Reinertsen (1997, p.71) goes so far as to argue for the benefits of design (test) failures because they contribute the most information regarding design problems and possible solutions. This raises questions about design process control, some of which have previously been addressed by this author (Ballard, 1999a).

Fourth and last, iteration in making is usually called "rework" and is clearly a type of waste to be avoided. Completing assigned tasks is a central principle of lean construction, both for the reduction in waste involved in making multiple visits to the same work location and for the plan reliability it increases, which has further positive impact on productivity and performance[4]. However, designing often requires the production of incomplete or provisional outputs in order to develop understanding of both design problems and alternative solutions (Lawson, 1997; Reinertsen, 1997; Ulrich and Eppinger, 1999). Designing can be likened to a good conversation, from which everyone leaves with a better understanding than anyone brought with them. How to promote that conversation (iteration) and how to differentiate between positive and negative iteration would appear to be critical design management skills. In the words of Fabio Pimenta[5], "Design development makes successively better approaches on the whole design, like grinding a gem, until it gets to the desired point; while construction happens in sequential phases which bring each part of the object to its finished state."

WHAT IS WASTE IN DESIGN?

Assuming that design is by its nature an iterative and generative process, how should we understand waste in design? Waste has been characterized by Koskela and Huovila (1997) in terms of minimizing what is unnecessary for task completion and value generation. Consequently, that iteration is wasteful which can be eliminated without loss of value or causing failure to complete the project. Precisely what iteration can be thus eliminated is a matter for empirical research. Informal surveys of design teams have revealed estimates as high as 50% of design time spent on needless (negative) iteration.

There are certainly other types of waste in design than negative iteration. One example is design errors. Reinertsen (1997, p.78) characterizes design outputs as defective when they fail because something previously known was forgotten or neglected. By contrast,

---

[2] However, there is the intriguing possibility of extending design into the making process, which certainly occurs in artistic production.

[3] Recognizing that the act of making can itself reveal the inadequacy of design, we should perhaps say that variability of outcomes is not desirable, so long as the requirements against which variation is judged are fit for purpose. If requirements are "quality", then conformance to those requirements generates value. It is important to remain alert for opportunities to generate better design or requirements even in the testing phases of final assembly.

[4] Ballard (1999a)

[5] Private communication (March, 2000) from Pimenta to Ballard commenting on this paper. Fabio Pimenta is director of Projetar, a mechanical and electrical engineering firm in Sao Paolo, Brazil.

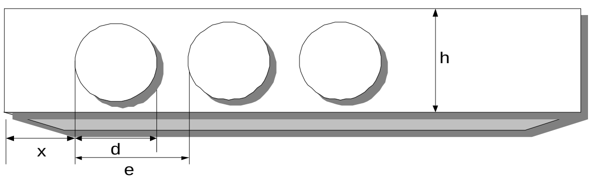
design outputs can be failures but not errors if they fail because of lack of knowledge not previously possessed.

REDUCING NEGATIVE ITERATION

BEAM PENETRATION CASE

Lottaz et al. (1999) tell a story illustrating negative (needless) iteration. Holes for refrigeration conduit were required in a beam (Figure 2). Primary dimensions were: 'd' (the diameter of a hole), 'e' (the distance between holes), 'x' (the distance from first hole to column), and 'h' (the depth of the beam).

The architect first specified values for the four dimensions then sent an annotated drawing to the steel fabricator, who changed the values for e and x and sent it on to the engineer. The engineer reduced the diameter of the hole (d) and sent the document back to the architect. Perhaps in a fit of pique, the architect reduced the value of x from 1100 mm to 1000 mm and finally involved the HVAC subcontractor, who made further changes and the cycle of changes and transmissions continued. The erection contractor was running out of time, so fixed values for the dimensions and had the beam fabricated. Unfortunately, he was then unable to persuade the team to accept his solution. The result was considerable time and money lost on the project.



Project Partner	d (mm)	e (mm)	h (mm)	x (mm)
Architect	550	650	650	500
Steel Fabricator	550	**900**	650	**1100**
Engineer	**200**	900	650	1100
Architect	200	900	650	**1000**
HVAC Subcontractor	**450**	**800**	650	**600**
Engineer	**400**	**900**	**730**	**700**
Steel Fabricator	400	900	730	**800**
.....	.....	.....	.....	.....

Figure 2 (taken from Lottaz et al., 1999): Beam Penetration Case

REDUCTION STRATEGIES

There are many contributors to the negative iteration in the beam penetration case. We might first question the sequence of design tasks. Was the architect the best person to establish initial values, then the fabricator, then the engineer, etc.? The *design structure matrix*[6] (DSM) is a device for eliminating or reducing iterative loops by resequencing

---

[6] The Lean Construction Institute (LCI), the University of California at Berkeley, and Loughborough University have a research agreement whereby ADePT has been combined with software produced at the University of California (by James Choo and Iris Tommelein) supporting the Last Planner system of

design tasks. It is one of several modules in the ADePT software developed at Loughborough University (Simon et al. (1999). DSM is appropriate when a specific design direction has been established or for the exploration of alternative design sequences. Once iterative loops have been minimized, this author proposes that selection be made from among the strategies presented below in order to manage each of those loops.

A major contributor is sequential processing, which adds to the time expended on the problem, but also actively hinders resolution. The architect (or anyone else) could have called a meeting to decide as a group on the values for the relevant dimensions. If the various contributors to the decision had been together in one place, at minimum there could have been an acceleration of the iterative looping. At best, there could have been genuine team problem solving. Using *cross-functional teams* and *team problem solving* to produce design is a staple of contemporary product development processes.

Table 2: Techniques for Reducing Negative Iteration

design structure matrix
team problem solving
cross functional teams
shared range of acceptable solutions (values)
share incomplete information
reduced batch sizes
team pull scheduling
concurrent design
deferred commitment
least commitment
set-based vs point-based design
overdesign

production control. LCI will apply the combined software to the management of U.S. design projects, Loughborough will apply it to U.K. design projects, and the results will be shared.

Many other concepts and techniques of advanced design management are relevant to the reduction of negative iteration. Suppose the participants had been willing to *share the range of values* acceptable to each. In that case, it would have been a simple matter to determine first if the problem as stated is solvable; i.e., if there are values for each dimension acceptable to all. They might have been unwilling to share that knowledge even if they were brought together face-to-face, in hopes that the final solution better favored them as opposed to others. Indeed, it appears to this author to be a routine of current design practice that supposedly collaborating specialists effectively compete for the priority of the values or criteria associated with their specialties.[7]

Willingness to share incomplete information has long been identified as a necessity for concurrency in design[8]. This can perhaps be best understood in terms of the lean production practice of *reducing batch sizes*, which belongs with DSM as a technique for restructuring the design process. Sequential processing results in part from the implicit rule that only completed design work is advanced to others. In terms of the beam penetration case, suppose the design team members agreed up front on work sequence, which would start by Team Member A providing just that information needed for Team Member B to calculate what he needs. B would in turn release that information to C, allowing C to do work, etc.

The Lean Construction Institute recommends producing such a work sequence by having the team responsible for the work being planned to work backwards from a desired goal; i.e., by creating a 'pull schedule'. Doing so avoids incorporation of customary but unnecessary work, and yields tasks defined in terms of what releases work and thus contributes to project completion. So doing reduces the waste of overproduction, one of the seven types of waste identified by Taiichi Ohno.[9] The Lean Design Group case described below is an excellent example of the benefits of implementing this strategy.

Deferred commitment is a strategy for avoiding premature decisions and for generating greater value in design. It can reduce negative iteration by simply not initiating the iterative loop. A related but more extreme strategy is that of *least commitment*; i.e., to systematically defer decisions until the last responsible moment[10]; i.e., until the point at which failing to make the decision eliminates an alternative. Knowledge of the lead times required for realizing design alternatives is necessary in order to determine last responsible moments. Such knowledge now tends to be partial or lacking.

When task sequence cannot be structured to avoid iterative looping, and when it is necessary to make a decision quickly, and when team problem solving is not feasible as a means of accelerating iteration, *design redundancy* may be the best strategy. An example: structural loads are not known precisely, but an interval estimate can be reliably produced. In that case, it might be decided to design for maximum load rather than wait for more precise quantification.

Posing alternative design solutions as sets, rather than as point solutions is the strategy at the heart of the method of *set-based design* (SBD). The beam penetration case is described by Lottaz et al. in order to present a technique and software for specifying ranges of values for continuous variables and modeling the solution space resulting from the intersection of alternative ranges. This approach has two roots, one theoretical and one

[7] Ballard (1999b).
[8] Clark and Fujimoto (1991).
[9] Ohno (1988).
[10] I first heard this expression in a Lean Construction Institute workshop for BAA in London in 1998, but do not know its origin.

from practice. The Lottaz paper emerged from the domain of artificial intelligence and the attempt to develop concepts and techniques for solving problems involving multiple constraints, exploration of which is beyond the scope of this paper. The other root is Toyota's method of managing product development processes.

SET-BASED DESIGN

The term "set-based concurrent engineering" was introduced by Ward et al. (1995)[11] as a name for Toyota's method of managing product development processes. We use the equivalent term "set-based design" (SBD).

Toyota's design practice is contrasted to point-based design, said to be characteristic of all other automobile product development firms, and arguably of most designing/engineering without regard to industry sector. In all design processes, alternatives are generated, evaluated, and selected. It is ordinary practice to select the best alternative as quickly as possible, then proceed to the next level of detail or decision and repeat the process.

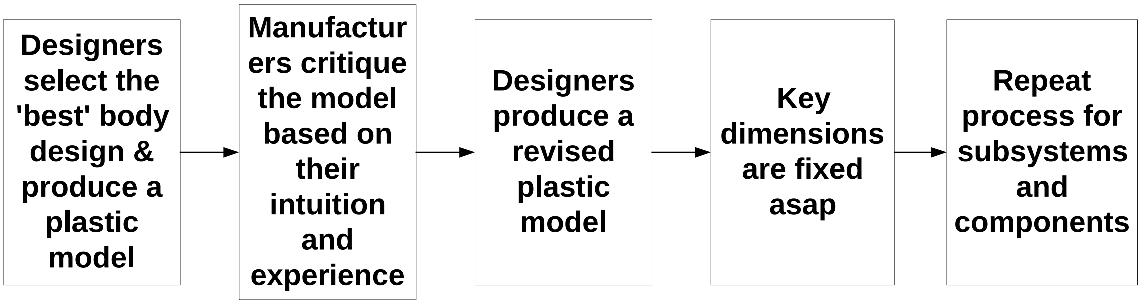


Figure 3: Point-based Design

Why might this be standard practice? In seminar discussions and classes, participants have suggested that they do not want to waste time on designs that will not be used, that they don't have time to carry forward multiple alternatives, and that they see no reason to 'dilly dally' once the best alternative has been identified. These reasons for practicing point-based design seem plausible, but raise the questions:

1) How is it that Toyota "wastes time" on designs not used and yet develops new products faster and cheaper (in development costs) than their competitors?

2) How do we decide when we have or do not have time to carry forward multiple alternatives?

3) Can we identify the best alternative immediately, without the benefit of further detailing and development?

One hypothesis regarding Toyota's superior performance is that their practice of carrying alternatives forward reduces negative iteration, and that the reduction is more than sufficient to offset time "wasted" on unused alternatives.

As regards having the time to carry alternatives forward, that would seem to be a function of understanding when decisions must be made lest we lose the opportunity to

[11] The term "set-based concurrent engineering" is not used by Yazdani (1999), but his "dynamic" model of the product development process appears to be virtually identical to Ward and Sobek's "set-based" models (Ward et al., 1995; Sobek et al., 1999).

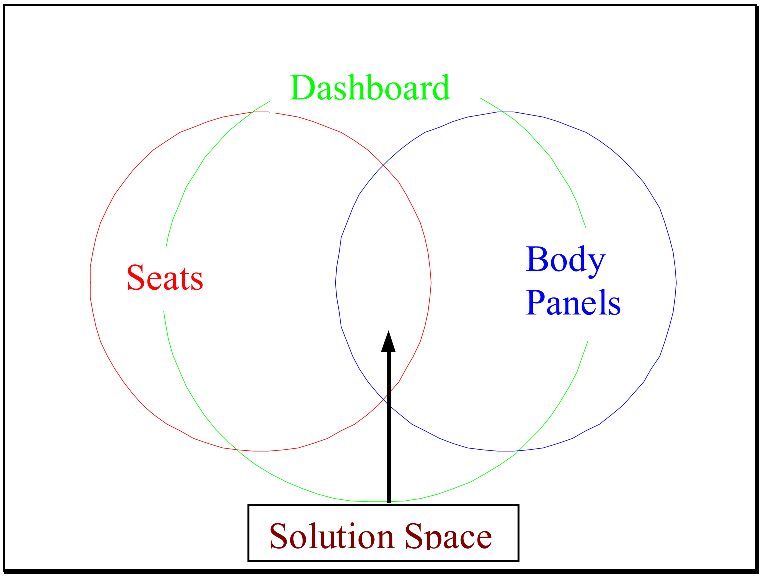
select a given alternative. We need to know how long it takes to actually create or realize an alternative. Understanding its variability, we can add safety-time to that lead-time in order to determine the last responsible moment.[12]

It is perhaps apparent that choosing to carry forward multiple alternatives gives more time for analysis and thus can contribute to better design decisions. The rush to narrow to a single alternative appears to us to be motivated most often by habits of thinking and action inculcated in traditional education and industry practice, although lack of memory capacity may also be a constraint (e.g., see Tommelein et al., 1991).

Three of the four authors of the original paper (Ward et al.) on Toyota's product development practice published a second paper last year (Sobek et al. 1999), in which they presented the principles of SBD:

1. Map the design space.
2. Integrate by intersection.
3. Establish feasibility before commitment.

Mapping the design space is identifying the set of alternatives or range of values to be carried forward. All design contributors are freed to develop their work, as long as they stay within those boundaries; i.e., within that 'design space'. *Integrating by intersection* means looking for solutions within the intersections of sets or intervals. For example, various interface dimensions can be specified for mating components such as seats, dashboards, and body panels (see Figure 4). The search for solutions is focused on the shared values for those dimensions. *Establishing feasibility before commitment* refers to the obligation of a design contributor to maintain consistency with the preexisting design. This is radically different from point-based design, in which each design contribution may invalidate all previous work. As an example, consider the beam penetration case presented above.



[12] There appears to be an opportunity for alternatives such as concrete and steel superstructures to compete on lead time. Shorter, less variable lead times would allow delaying design decisions to accommodate customer needs for late-breaking information, or could be used to shorten overall project durations.

Figure 4: Integrate by Intersection

SBD is said to have many benefits: The following list is drawn from the papers by Ward and Sobek:

1. Enables reliable, efficient communication.
   -Vs point-based design, in which each change may invalidate all previous decisions.
2. Waste little time on detailed designs that can't be built.
3. Reduces the number and length of meetings.
4. Bases the most critical, early decisions on data.
5. Promotes institutional learning.
6. Helps delay decisions on variable values until they become essential for completion of the project.
7. Artificial conflicts and needless iterations of negotiations are avoided.
8. The initiator of a change retains responsibility for maintaining consistency.

LEAN DESIGN GROUP OF SÃO PAULO

The Lean Construction Institute (LCI) is a business partner in a newly formed design firm in São Paulo, Brazil. The Lean Design Group consists of LCI, CFA (architectural), Projetar (mechanical and electrical engineering), Gramont (civil/structural engineering), and PIC (production management). The principals are Greg Howell (LCI), Glenn Ballard (LCI), Henrique Cambiaghi (CFA), Fabio Pimenta (Projetar), Francisco Graziano (Gramont), and Federico Orecchia (PIC).

The Lean Design Group recently began to experiment with lean design techniques suggested to them by this author. They first tested the basic idea (which they termed "set-based design") on several design firms in the area. The idea was to depart from their traditional practice of producing only completed design outputs, and rather share incomplete information as needed by others to get started. "When the method was explained, all of them ended up not only to agree with the concept but also got enthusiastic and helped list advantages…." "…we got the sensation of "how in hell didn't we think of this before-it's obvious!"[13]

Based on these preliminary discussions, the advantages expected were: 1) reduced design duration and cost by doing design work more concurrently, the key to which would be reducing the batch size; i.e., producing incomplete information, but sufficient to release work to someone else. 2) increased design efficiency from better communications among members of the design team.

They then prepared to try out this new approach on the design of a series of supermarkets. The relevant planning actions were:

- "…each task was programmed to begin as soon as there is enough input data to permit the beginning of any conceptual work…."
- "We defined, for each task, what were the real goals of the task, which piece of information is really needed by other teams, and what is the tolerance that may be accepted, so that every team may work exactly on what matters to it."

[13] All quotes in this section are from a private communication-Pimenta to Ballard, 3/25/00.

-The design schedule thus produced was adjusted to "…result in continuous work, so that our team can be kept the same, working continuously from the beginning until the end of the design…."

Results expected include:

-Reduction in design time from 90+ days to 46 days

-Engineers will be able to begin working 2 days after the architect starts rather than waiting 25 days for preliminary plans

-4 coordination meetings versus 12

-Between 2 and 7 people will be working on the project at any given time, and none of them will work less than 14 days. This contrasts will previous projects, on which the team varied from 1 to 11 people, some of whom worked no more than 2-3 days in total.

-labor hours reduced by 25-30%

-"Decision-making will turn out to be an objective, well organized process, in which all the possible alternatives and factors of all the teams are taken into account, instead of a sequential, isolated process, in which decisions are made separately by each of the teams, only taking into consideration their own convenience, and not the impact of the decision on the other teams."

Application of these plans and testing of these expectations was to have begun in April 2000 and will be published as soon as possible.

CONCLUSIONS

Negative iteration is an important source of waste in design, but can be reduced by the application of techniques such as team problem solving, design structure matrix, batch size reduction, least commitment, and set-based design. These techniques seem to fall into categories: restructuring the design process, reorganizing the design process, managing the design process differently than traditionally, and lastly overdesigning, when there is no better solution (Table 3).

Table 3: Strategies for Reducing Negative Iteration

❑ Restructure the design process -use DSM to resequence -use pull scheduling to reduce batch sizes and achieve greater concurrency
❑ Reorganize the design process -make cross functional teams the organizational unit -use team problem solving (call a meeting) -share ranges of acceptable solutions
❑ Change how the design process is managed -pursue a least commitment strategy -defer this decision (defer commitment) -practice set-based design -use the Last Planner system of production control

- Overdesign (design redundancy) when all else fails

Much exciting research is needed to develop the techniques identified thus far and to develop new techniques. This author intends to experiment with all the techniques and strategies discussed in the paper, but initial emphasis will be on the application of the design structure matrix, organizing around cross functional teams, reducing batch sizes in design, applying Last Planner to design, and practicing a least commitment strategy. Some of this research will be done in collaboration with other research institutions, such as the University of California at Berkeley, Loughborough University, Stanford's Center for Integrated Facilities Engineering, and the Centre for Construction Innovation at the University of New South Wales. Some will be done through our Lean Design Group in Brazil and through member companies of our Lean Construction Institute. Some will be done through research-minded industry practitioners such as Frank McLeod of WSP/BAA.

In addition to the areas mentioned, work is needed to better understand and exploit the contributions of artificial intelligence to this issue of reducing negative iteration and to design management generally.

Finally, in parallel with work on reducing negative iteration, research is also underway on generating value through promoting positive iteration, to which several of the techniques and strategies discussed are relevant; e.g., the organizational strategy of cross functional teams. The focus of the value generation research is on the project definition process, and minimizing value loss through better control of handoffs. Researchers interested in any or all of these issues are emphatically invited to collaborate.

REFERENCES

Alarcon, L. (editor) (1997). *Lean Construction*. A.A. Balkema, Rotterdam, The Netherlands, 497 pp.

Austin, S., Baldwin, A., Li, B. & Waskett, P. (1998) "Analytical Design Planning Technique (ADePT): A Dependency Structure Matrix Tool to Schedule the Building Design Process." *Construction Management and Economics*, December, 1999.

Ballard, Glenn (1999a). "Improving Work Flow Reliability". *Proceedings of the 7th Annual Conference of the International Group for Lean Construction,* University of California, Berkeley, CA. p. 275-286. <http://www.ce.berkeley.edu/~tommelein/IGLC-7>

Ballard, Glenn (1999b). "Can Pull Techniques Be Used In Design?" *Proceedings of the Conference on Concurrent Engineering in Construction*, Espoo, Finland, August 1999. 18 pages.

Clark, Kim B. & Fujimoto, T. (1991). *Product Development Performance,* Harvard Business Press, Cambridge, MA.

Juran, Joseph, and Gryna, Frank M., Jr. (1986). *Quality Planning and Analysis.* McGraw-Hill, New York.

Koskela, L. & Huovila, P. (1997). "On Foundations of Concurrent Engineering" in Anumba, C. and Evbuomwan, N. (eds.). *Concurrent Engineering in Construction CEC97*. London 3-4 July. The Institution of Structural Engineers, London, 22-32.

Koskela, L., Ballard, G., and Tanhuanpaa, Vęli-Pękka (1997). “Towards Lean Design Management”. *Proceedings of the 5th annual conference of the International Group for Lean Construction,* Gold Coast, Australia. <http://cic.vtt.fi/lean>

Lawson, Bryan (1997). *How Designers Think, 3rd edition.* The Architectural Press Ltd., London, U.K.

Lottaz, Claudio, Clément, Denis E., Faltings, Boi V., and Smith, Ian F. C. (1999). “Constraint-Based Support for Collaboration in Design and Construction”. *Journal of Computing in Civil Engineering,* ASCE, New York, 23-35.

Ohno, Taiichi (1988). *Toyota Production System: Beyond Large-Scale Production.* Productivity Press, Cambridge, Massachusetts. (Translation not credited.)

Pimenta, Fabio (2000). Personal communication to Glenn Ballard.

Reinertsen, Donald G. (1997). *Managing the Design Factory.* The Free Press, New York. 269 pp.

Sobek, Durward K. II, Ward, Allen C., and Liker, Jeffrey K. (1999). "Toyota's Principles of Set-Based Concurrent Engineering." *Sloan Management Review*, Winter 1999.

Tommelein, I.D., Levitt, R.E., Hayes-Roth, B., and Confrey, T. (1991). "SightPlan Experiments: Alternate Strategies for Site Layout Design" *Journal of Computing in Civil Engineering*, ASCE, Vol 5, No. 1, pp 42-63.

Ulrich, Karl T. and Eppinger, Steven D. (1999). *Product Design and Development,* 2nd edition. McGraw-Hill, NY, NY.

Ward, Allen, Jeffrey K. Liker, John J. Cristiano, and Durward K. Sobek II (1995). “The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster”. *Sloan Management Review,* Spring 1995, pp. 43-61.

Yazdani, Baback and Holmes, Christopher (1999). "Four Models of Design Definition: Sequential, Design Centered, Concurrent and Dynamic". *Journal of Engineering Design,* Vol 10, No. 1.