

Adding Value: An Architect's Retaliation against the Mortgage Industry  
and a Computational Investigation into Do-It-Yourself Design-Build

by

Dennis Michaud

B.A., Art History (2004)

Trinity College, Hartford

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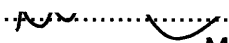
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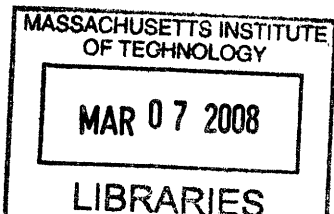
  
Department of Architecture  
January 17, 2008

Certified by.....

  
Mark Goulthorpe  
Associate Professor of Architecture  
Thesis Supervisor

Accepted by.....

  
Julian Beinart  
Professor of Architecture  
Chair of the Department Committee on Graduate Students



ARCHIVES

Readers:

Adèle Naudé Santos  
Dean of the School of Architecture

Lawrence Sass  
Associate Professor of Architecture



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AGAINST THE MORTGAGE INDUSTRY AND A  
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ABSTRACT

This thesis proposes a novel system for the design, fabrication, and assembly of the single-family home. Driven by the American mortgage crises of the early-20<sup>th</sup> Century, the proposal selects for its client-type the foreclosed ex-homeowner and thus the constraint of a mortgage-free homeownership solution. The thesis presents a holistic view of residential architecture, taking into account the social, economic, technical, and geographical constituents comprising the current realities and the present possibilities of American homeownership.

Specifically, this thesis demonstrates the technical possibility for a do-it-yourself design and assembly system for the mass-customized expansion of a single-family over its lifetime and the positive effects of such customization at the level of the suburban development.

Thesis Supervisor: Mark Goulthorpe

Title: Associate Professor of Architecture

## **ACKNOWLEDGEMENTS**

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## PROBLEM (MANIFESTO)

In 1934, the Roosevelt Administration passed the Federal Housing Act in response to the post-war housing crises in the United States.<sup>1</sup> The ostensible goal of this measure was clear: to allow more Americans entry into homeownership<sup>2</sup> by increasing the availability of large, individual loans for the purchase of a house.<sup>3</sup> From this point forth, purchasing a home with a mortgage has served to greatly augment homeownership in the United States<sup>4</sup> and has indeed become the common praxis for achievement of the American Dream.<sup>5</sup>

The Federal Housing Act, however, failed. What was once incredibly effective at creating an efficient free-market solution to the post-war housing crises in the United States<sup>6</sup> has become a monopoly<sup>7</sup> that liberally force-feeds houses to American homebuyers without regard to the real needs of the perspective inhabitants - all under the guise of a "secure investment."<sup>8</sup>

A house is a place to live, not a financial tool.

Recent revelations in the home building industry (which will be said to include the speculative development, mortgage, and real estate industries) have shown that this triumvirate structure is now ineffective at producing homes that a large percentage of Americans can actually afford.<sup>9</sup> The subprime mortgage<sup>10</sup> meltdown<sup>11</sup> is simply

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<sup>1</sup> Knerr, Chapter 1

<sup>2</sup> Homeownership, particularly in suburban environments, was said to "encourage[] stability and patriotism as well as productivity." (Knerr, p. 27)

<sup>3</sup> Knerr, Chapter 1

<sup>4</sup> Knerr, Chapter 1

<sup>5</sup> Kelly(2), p. 27 & Lord, p. 16

<sup>6</sup> by generating ample capital and tangible value in housing

<sup>7</sup> "An easy and politically convenient solution to this problem is a policy of subsidization of either the industry or the consumer. This subsidization results in the diversion of resources from other chronically underfunded areas of high national priority – such as health, welfare, environmental quality, or education – and must continue as long as there is a need for increased production. Subsidization in this form fails to provide incentives for the sector to improve its responsiveness to the needs and desires of the consuming population or to reduce the cost of production of shelter." (Bernhardt, p. 5)

<sup>8</sup> The purchase of a home is consistently touted by the Real Estate Industry as a "secure investment in ones future," as well as by the Mortgage Industry towards Wall Street as a "secure investment" mechanism. (Kelly(2), p. 20)

<sup>9</sup> "[T]he building industry here and abroad still is not equipped to respond adequately to what has long since grown into a building and housing crises. The industry's performance is suboptimal: It produces shelter of higher cost and/or lower quality than it potentially can[...]" (Bernhardt, p. ix)

<sup>10</sup> Subprime mortgages are loads extended to homebuyers with "poor" credit or repayment potential for the purchase of a house. The rapid proliferation of subprime

one piece of evidence that the homebuilding industry cannot, in an honest manner, match the much earlier achievement of Henry Ford: unlike nearly every other industry in the United States, the homebuilding industry has failed to industrialize.<sup>12</sup> This does not necessarily mean the mass production of a high volume of houses, rather, at its most basic, it demands the rationalization of the connection between housing needs and the efficient production of their fulfillment.<sup>13</sup>

Therefore, an industrialized solution can be said to succeed, at least in design, to the degree that it accurately responds the needs of the market. If not - it fails: no one buys it, and design evolution occurs in a free-market, self-regulating fashion...

---

mortgages in the United States began in the 1990s, when between 1994 and 1998, for example, the subprime market expanded from \$35 million to \$150 million, with ten times the amount of loan extended. (Lord, p. 17)

The reason for this rapid increase in these highly risky loans are due to the following factors:

1. Wall Street subsidizing these loans through "mortgage-backed securities": financial products (like stocks and bonds) that gain and lose value based on the interest rate of a "packaged" group of mortgages and their repayment or lack of repayment by the homeowners. (Lord, p. 19)
2. The ability of mortgage brokers to levy high (often hidden and often increasing) fees and interest rates on the homeowners for the extension of a subprime loan. (Lord, p. 21)
3. The perceived of the real estate/mortgage markets. (Lord, p. 20)

<sup>11</sup> At the time of this thesis, the proliferated extension of subprime mortgages had finally burst into a market plunge the negative economic effects of which continue to expand and reverberate throughout the United States and abroad. Put simply, at the root of the subprime mortgage meltdown is a mortgage lending practice called "predatory lending." Predatory Lending is a method of coercing, typically, certain socio-economic groups of people into accepting mortgages that their personal credit value should not allow and that their economic status cannot afford. Predatory subprime mortgages lenders, through a technique called "negative redlining," select groups of people to whom traditional, reliable banking institutions may not extend loans and "sell" them a loan. The victims are tricked into loans that carry exorbitantly high fees and interest rates, as well as other unethical money-extraction clauses such as "early-payoff fees" and "balloon payments." (See Lord, *American Nightmare: Predatory Lending and the Foreclosure of the American Dream* for an in-depth explanation and series of illuminated case studies on the issue.)

<sup>12</sup> "The housing industry," Knerr (*Suburban Steel*) notes, "had not matured in an industrial or societal sense. It had not produced a product suited to the needs of the mass market. It had not followed the Ford model of industrial progress. In short, capitalism failed the housing industry, and the housing industry had failed capitalism." (Knerr, p. 34) This is incredible for an industry itself accounting for around 10% of the nation's Gross National Product (GDP) (Bernhardt, p.xi)

<sup>13</sup> Bernhardt, p.xi

Not in the building industry! Here, banks and investors already finance the creation of homes prior to the need.<sup>14</sup> These homes are nose-pinch-swallowed by Americans because, unlike designs that precisely suit the unique needs and desires of the buyer, generic houses are able to attract banks willing to extend a mortgage for a house easily resold if the home-“owner” is unable to make their monthly payments. Ensuring the continuity of this simulacrum of demand, the real estate industry gleefully plays with the values of these homes. In other words, by virtue of this tripartite monopoly, the homebuilding industry is able to produce whatever design it can throw onto suburban plots because investors will fund their doing so. Furthermore, the real estate industry is happy to sell these low-quality, mass-produced shells as appreciable, secure investments (while it simultaneously pushes “the newest thing” that will make the older houses obsolete). And finally, Wall Street makes sure<sup>15</sup> there is ample quantities of extremely expensive<sup>16</sup> “free money” floating around to entice home buyers into accepting a mortgage for purchase of the biggest house possible (because, of course, “you have to think of the future”).

This bloated system creates unacceptable waste. Essentially, homebuyers are obliged to purchase larger and larger homes in order to make a buckshot attempt to capture, somewhere in those extra, ambiguously programmed giga-spaces, all of their needs and desires. We “have it your way”<sup>17</sup> hamburgers, but our houses come with all of the fixings super-glued to the buns - and somewhere in there, amid all the wasted square footage of living rooms, dens, “rec.” rooms, etc. is what the inhabitants actually need.

At the writing of this thesis, the American housing system is in crises. Suburban landscapes are polluted by large chunks of homogenous houses – supersized reminders that, not only is the current building industry incapable of fulfilling the single-family housing demands of the average American, the Finance—Construction—Real-estate monopoly that has forced the under-classes into loans—houses—investments far larger than they can afford<sup>18</sup> is now taking these homes back,<sup>19</sup> along with the livelihood of a rapidly increasing number of foreclosed ex-homeowners. Ultimately, the American mortgage crises of the early 21<sup>st</sup> Century makes clear one inescapable fact: the 1934 Federal Housing Act, upon which nearly the

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<sup>14</sup> Suburban developments are very often leveraged and speculative, in that capital for the construction of the development is borrowed from a financial institution for the construction of the development *prior to* ascertained demand.

<sup>15</sup> Lord, p. 19

<sup>16</sup> See Lord, *American Nightmare*, for an in-depth discussion of the overall *cost* of a mortgage to, especially, subprime borrowers.

<sup>17</sup> © Burger King Corporation

<sup>18</sup> <sup>18</sup> See Lord, *American Nightmare*, for case studies supporting this claim.

<sup>19</sup> At the writing of this thesis, foreclosure rates are expanding at an alarming rate throughout the United States.

entire system of American homeownership is supported, has failed to provide a real and sustainable solution for housing without compromising two of the primary benefits of homeownership – stability and individuality.

## BACKGROUND

The industrialization of the single-family home is not a new concept. In 1830 in Britain, John Manning developed the "Manning Portable Cottage," a factory produced *kit-of-parts*<sup>20</sup> for shipment to British colonies in Australia and South Africa.<sup>21</sup> (Figure 1) Across the Atlantic, Augustine Deodat Tayler, a Chicago carpenter, invented the *balloon frame* construction technique at St. Mary's Church on Lake Street in 1933.<sup>22</sup> While built on-site with relatively traditional tools, this new system for rapid and low-skilled erection of small wood-frame structures was developed and made possible by industrialized advances in sawn lumber, of which Chicago was the center.<sup>23</sup> Because of its simple but efficient method of using standardized studs, low-tech outdoor "factories" of unskilled workers could be employed to rapidly build houses, and in 1834 alone one-hundred and fifty houses were built!<sup>24</sup> The age of the industrialized, single-family home had begun.

Beginning in the mid-1940s, the US federal government began a second measure towards the goal of increasing homeownership:<sup>25</sup> through subsidized loans, government-sponsored programs such as the Veteran's Emergency Housing Act (VEHA) and the Reconstruction Finance Corporation (RFC) provided support and sponsorship to private companies involved industrializing the process of homebuilding.<sup>26</sup> One of the major beneficiaries of this government sponsorship was the Lustron Corporation,<sup>27</sup> founded by Carl Strandlund in 1946.<sup>28</sup> Southerland, previously involved in the use of enameled steel for commercial construction, transformed this knowledge into creating the home of the industrialized future.<sup>29</sup> (Figure 2) The single-family houses produced by the Lustron Corporation survive today as some of the finest examples of industrialized housing.<sup>30</sup> Their hardy enamel steel shells and innovative integration of structure and services<sup>31</sup> are still enjoyed by their inhabitants,<sup>32</sup> and the image of the Lustron

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<sup>20</sup> For a description of "kit-of-parts" systems, see Eastman, pp. 27-28.

<sup>21</sup> Davies, p. 47

<sup>22</sup> Davies, pp. 45-46

<sup>23</sup> Davies, p. 46

<sup>24</sup> Davies, p. 26

<sup>25</sup> Knerr p. 10

<sup>26</sup> Knerr, p. 9

<sup>27</sup> The Lustron Corporation benefited from over \$40 million in government loans, greatly exceeding the amount received any other prefabricated venture of the time. (Knerr, p. 9)

<sup>28</sup> Knerr, p. 13

<sup>29</sup> Knerr, p. 13

<sup>30</sup> "Clearly the design and quality of Lustron's product," Douglas Knerr (*Suburban Steel*) notes, "demonstrated that many Americans would accept a factory-made house, a significant accomplishment given previous perceptions of prefabricated houses as cheap, impermanent "crises" housing." (Knerr, p. 184)

<sup>31</sup> Knerr, p. 103

<sup>32</sup> Knerr, p. 182



lifestyle,<sup>33</sup> as manufactured by the company's marketing, survives today as the quintessential picture of 20<sup>th</sup> century American domesticity. (Figure 3)

Nonetheless, the Lustron Corporation, heavily bolstered by the federal government, fell victim to an early public execution during the cold war, sacrificed to placate public outcry against "creeping socialism" by the same Truman Administration that had previously nurtured the company.<sup>34</sup> In terms of its effect on the post-war housing crises, the Lustron House was not very different a solution than the Federal Housing Act, although its monopolizing potential was caught far sooner. As a top-down solution from its inception, the Lustron Corporation lacked the flexibility and sensitivity of economic flux that, in the opinion of the author, is necessary to provide a truly affordable, single-family housing solution.

Founded in 1942 by Walter Gropius and Konrad Wachsmann, the General Panel Corporation created one of the most advanced systems for industrialized, site-assembled, single-family housing.<sup>35</sup> The result of a career's worth of research in the industrialization of building for both architects, the product was extremely sophisticated, elegant, and versatile: the *Packaged House*.<sup>36</sup> (Figure 4) A catalogue of possible designs for the system was created for distribution (Figure 5), and an enormous factory capable of producing ten-thousand houses per year was built.<sup>37</sup> (Figure 6) By all technical measures, the Packaged House was one of the most flexible and elegant solutions to industrialized single-family housing ever created (Figure 7); by any measure economics, it was an absolute failure. While the homebuilding industry was busy building literally thousands of *prefabricated* homes per month, Gropius and Wachsmann barely produced a respectable number of demonstration houses.<sup>38</sup> Like the Lustron House, the failure of the Packaged House was not one of design, but of top-down hierarchies: Wachsmann, the primary designer of the system, was more interested in *the* perfect, single solution, that market and economic demands were almost completely ignored.<sup>39</sup>

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<sup>33</sup> Knerr, p. 109

<sup>34</sup> Knerr, p. 12

<sup>35</sup> Built of universal panels and easy-to-assembly joints, it was able to be assembled on a pre-laid foundation by five unskilled workers in one day. (Davies, pp. 23-24)

<sup>36</sup> Davies, p. 19

<sup>37</sup> Davies, pp. 19-21

<sup>38</sup> Herbert Gilbert (*The Dream of the Factory-Made House*) reveals that only 150 to 200 Packaged Houses were produced (far from Wachsmann's goal of 10,000 per year), and of those, not many more than 15 houses were actually sold. (Herbert, pp. 301-304)

<sup>39</sup> "For Wachsmann, the Packaged House was not really a house, not a locus for the lives of real people, not even 'a machine for living in'; it was an abstract geometrical system, tending always towards mathematical perfection. Wachsmann was obsessed with his system and could never stop 'improving' it, which meant making it

Between 1947 and 1951, development firm Levitt and Sons built 17,500 houses on New York's Long Island.<sup>40</sup> "Levittown," as it was called, is perhaps the most emblematic example of the lower/middle-class<sup>41</sup> American single-family development.<sup>42</sup> (Figure 8) What Levitt and Sons provided was indeed minimal: a moderate sized plot of land and a small house. New residents had two choices of houses: the "Ranch House" and the slightly larger "Cape Cod,"<sup>43</sup> a result of the innovative Mass Production system employed by Levitt and Sons to keep costs as minimal as possible in a (successful) effort to extend homeownership to a broader range of Americans. While no formal factory existed, the development firm transferred the Long Island land into a large-scale outdoor production facility. However, Levittown went beyond providing affordable, single-family homeownership to under-class Americans; it provided a framework from which to literally build their selves up to the middle-class. Both of Levittown's houses were designed to facilitate expansion over time.<sup>44</sup> Thus, with "sweat equity," many Levittown homeowners could transformed their minimal "starter homes" in true, middle-class houses; and by 1967, the development was accepted into the middle-class by everyone from census data collectors to its initially disapproving middle-class neighbors.<sup>45</sup> Expansions were not simply the addition of more space, but, more importantly, the adaptation of the homes for changing needs, such as growing families, automobile purchases, and aging family members.<sup>46</sup> (Figure 9) As a dynamic system that allowed for growth and adaptation to suit the actual needs of and on the independent terms of the owners, Levittown, more than perhaps any other well-known example of 20<sup>th</sup> century single-family housing innovation, truly expressed the potential social benefits possible with the sensitive application of industrialization principles in single-family dwelling.

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conceptually as near perfect as he could[...] His satisfaction came not from the production of thousands of houses or the alleviation of a housing crises, or even from the financial rewards that commercial success would bring; it came from the design of a perfect abstract system." (Davies, p. 24)

In Gilbert Herbert's book *The Dream of the Factory-Made House*, Herbert blames society for the failure of the Packaged House, calling for "a society more amenable to logical discourse, rational decision making, and creative human interaction than we at present appear to be." (Herbert, p. 325)

<sup>40</sup> Kelly(2), p. 27

<sup>41</sup> Kelly(2), p. 27

<sup>42</sup> Due, in part, to the growing socio-economic success of Levittown, "large, single-use, suburban tracts of small, low-cost, single-family, owner-occupied dwellings had merged into a new by the end of the 1940s." And, "in the fall of 1957, a number of newspapers and magazines revisited the ten- year-old Levittown." (Kelly(2), p. 28)

<sup>43</sup> Kelly(2), p. 29

<sup>44</sup> Kelly(2), pp. 28-31

<sup>45</sup> Kelly(2), p. 27

<sup>46</sup> Kelly(2), pp. 29-31



At around the same time,<sup>47</sup> a second truly successful venture into the industrialization of single-family housing would push beyond the bar of innovation set by the Levitt and Sons model.<sup>48</sup> The *manufactured home*, also called the "caravan," the "trailer," and the "mobile home," began in the United States as a modern fetish for the vacationing class: its first examples were intended to bring all of the modern luxuries of the home to wherever one vacations.<sup>49</sup> However, by the 1940s,<sup>50</sup> a critical mass of permanent "mobile home" inhabitants began to raise fundamental questions about what a house is and the role of industrialization within it. For whatever reason the stigma against manufactured homes<sup>51</sup> exists, at least through the downcast eyes of the upper classes, it cannot justifiably be based on quality – due to the precision afforded by the factory environment in which manufactured homes are produced, most are of equal or superior quality to their site-built counterparts.<sup>52</sup> Indeed, perhaps the only valid reason for the prejudice of the site-built homeowner against the manufactured home-dweller is that the latter paid far more for a product that is of inferior quality.<sup>53</sup>

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<sup>47</sup> Colin Davies (*The Prefabricated House*) traces the origins of the mobile home in America to the Tin Can Tourists of the 1920s, a group of vacationing families who camped out of their Model T Fords bringing with them, naturally, (tin) canned food (among other things). It was not until the 1940s, years after people had begun making permanent residences of their mobile homes, that the mobile home gained enough critical mass to be considered a real housing alternative. (Davies, pp. 73-74)

<sup>48</sup> "[T]he mobile home industry[ has evolved] into the most efficient shelter industry in the world." (Bernhardt, p. x)

<sup>49</sup> Davies, p. 74

<sup>50</sup> Davies, p. 74

<sup>51</sup> Colin Davies (*The Prefabricated House*) explains: "An important part of [marketing of mobile homes] was a change of name. 'Trailer' meant temporary housing for poor people. It had to go. In 1953 the Trailer Coach Manufacturers' Association became the Mobile Home Manufacturers' Association (MHMA). Twenty years later, 'mobile home' had picked up its share of negative associations and name inflation demanded another denomination. In 1975 in MHMA changed its name to the Manufactured Housing Institute, removing all reference to mobility and deliberately blurring its territorial border with the construction industry." (Davies, p. 78) Also see Bernhardt, p. x.

<sup>52</sup> Bernhardt, p. ix

<sup>53</sup> Colin Davies, in *The Prefabricated House*, offers an enlightening example of success of the mobile home and the close-minded aloofness that prevents its accomplishments from being acknowledged:

*'The mobile home by any other name', said [famed "industrialist" architect Paul] Rudolph, "could be a useful solution to the low-cost housing problem." Could be? Didn't he know that it already was? [...] The patronizing attitude is summed up in this extract from an Architectural Record article[...]:*

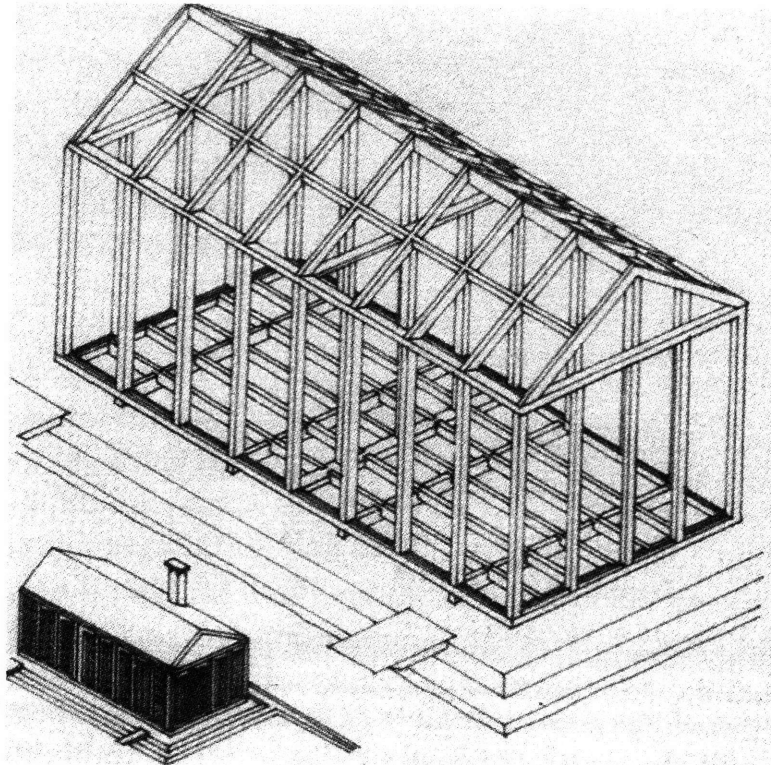


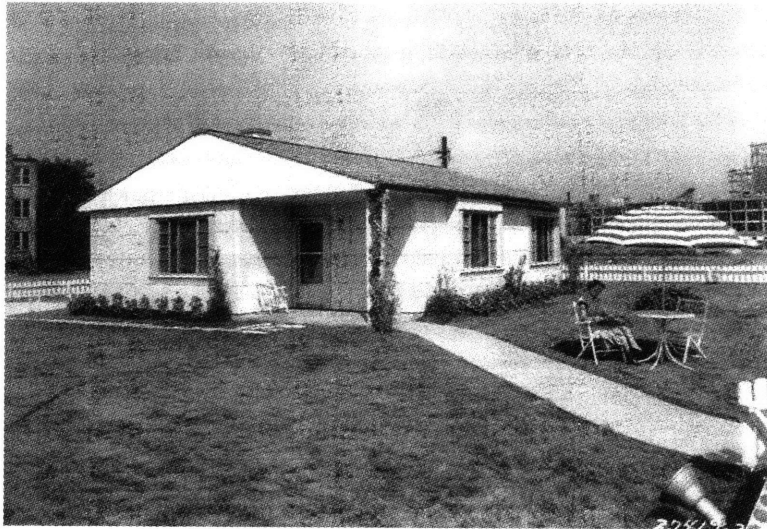
Figure 1 - Manning Portable Cottage  
(Image: Davies, p. 48)

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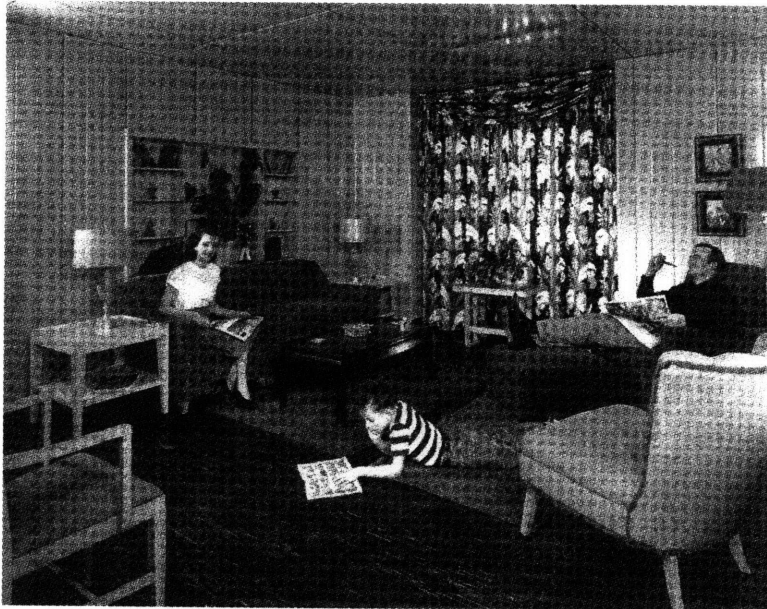
*Rudolph believes that given the opportunity to properly design, upgrade and test its product... the mobile home industry could become the leader in lightweight steel box frame technology, meeting this nation's and world's great need for handsome, well engineered, low-cost dwelling units.*

*This is the advice that the author of a handful of modular housing projects, all but one of them unbuilt, offers to an industry that was at the time building more than half a million affordable homes a year.*

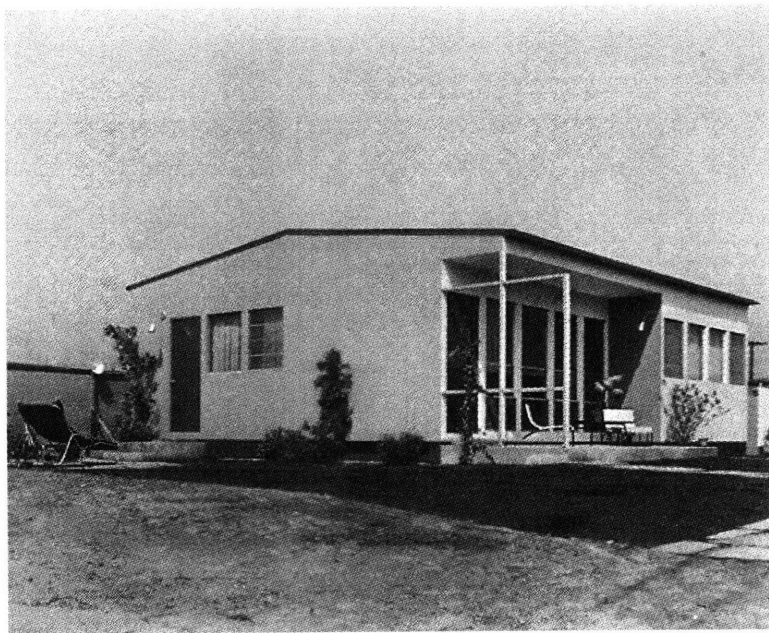
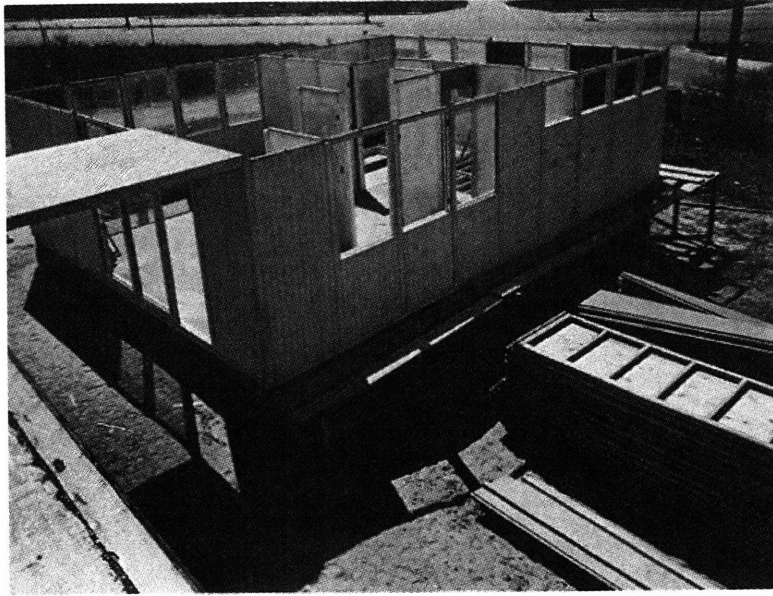
- Davies, pp. 86-87 (Also see Bernhardt, p. ix)



*Figure 2 – Lustron House  
(Image: Knerr, p. 79)*



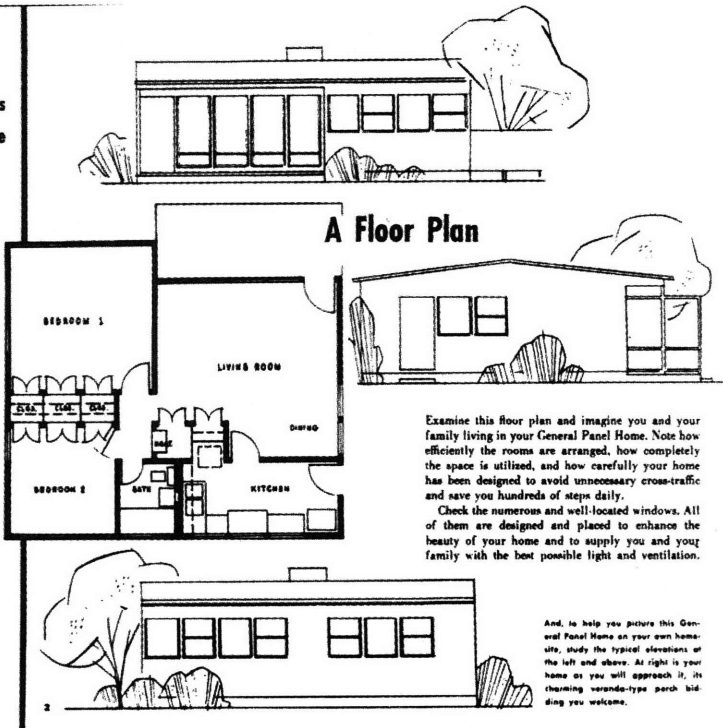
*Figure 3 – Lustron House (Marketing Image)  
(Image: Knerr, p. 79)*



*Figure 4 – Packaged House (Demonstration Model)  
(Image: Herbert, p. 282)*

**Check these quality features  
of your General Panel home**

- EXTERIOR FINISH**  
Finished with high-grade paint, in your choice of colors, over priming coat of moisture-resistant sealer.
- INTERIOR FINISH**  
Smooth walls, sealed against moisture, then painted or papered to your specifications.
- INSULATION**  
All exterior walls, interior partitions and ceilings are insulated to keep you cool in summer, warm in winter. Saves heating costs. Deadens sounds from outside and from within.
- CLOSETS**  
Large, well-placed closets supply an abundance of space for clothing, linens, blankets, storage.
- WINDOWS**  
Modern picture windows, with smooth-working, leak-proof and rust-proof aluminum window frames and screens.
- DOORS**  
Handsome flush-paneled doors. Hollow core for soundproofing; precision-hung to avoid sticking and drafts.
- FIXTURES**  
Nationally famous, high-quality electrical, hardware and plumbing fixtures throughout.
- PLUMBING**  
Machine cut and threaded pipe and copper tubing, precision fitted.
- HEATING**  
Centrally located wall-type heater of 45,000 B.t.u. input capacity keeps entire home warm. Remember, your General Panel home is INSULATED and keeps warm with less fuel.
- FOUNDATION**  
Fully approved continuous-wall-and-pier type concrete foundation.
- ROOF**  
Long-life composition roof, safer because it's fire-resistant.

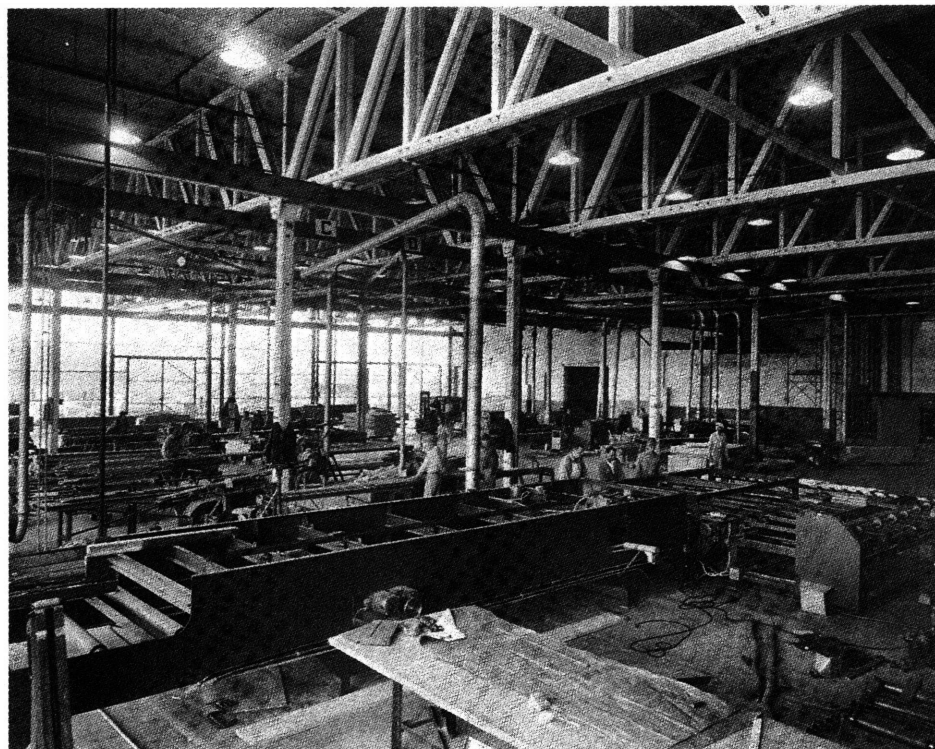


Examine this floor plan and imagine you and your family living in your General Panel Home. Note how efficiently the rooms are arranged, how completely the space is utilized, and how carefully your home has been designed to avoid unnecessary cross-traffic and save you hundreds of steps daily.

Check the numerous and well-located windows. All of them are designed and placed to enhance the beauty of your home and to supply you and your family with the best possible light and ventilation.

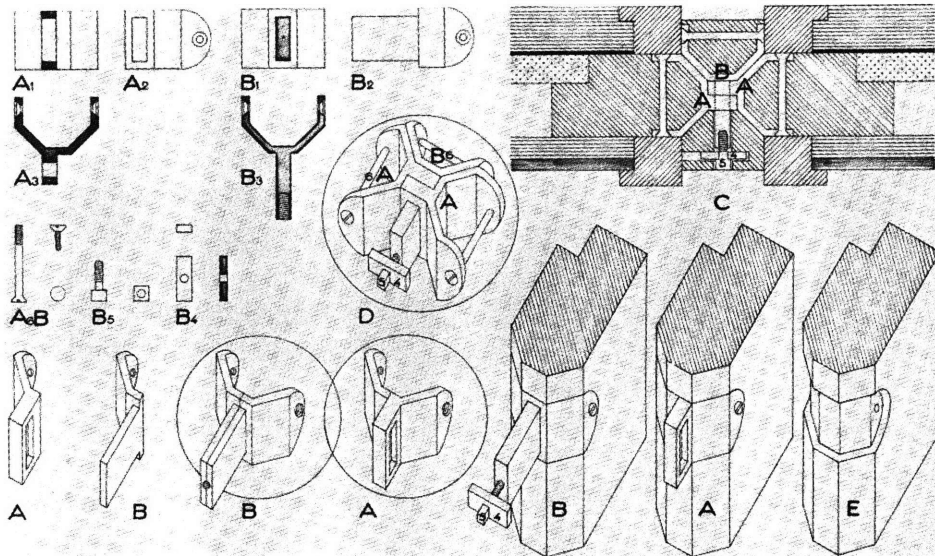
And, to help you picture this General Panel Home on your own home-site, study the typical elevations at the left and above. At right is your home as you will approach it, its charming veranda-type porch bidding you welcome.

*Figure 5 - Packaged House (Catalogue Page)  
(Image: Herbert, p. 295)*

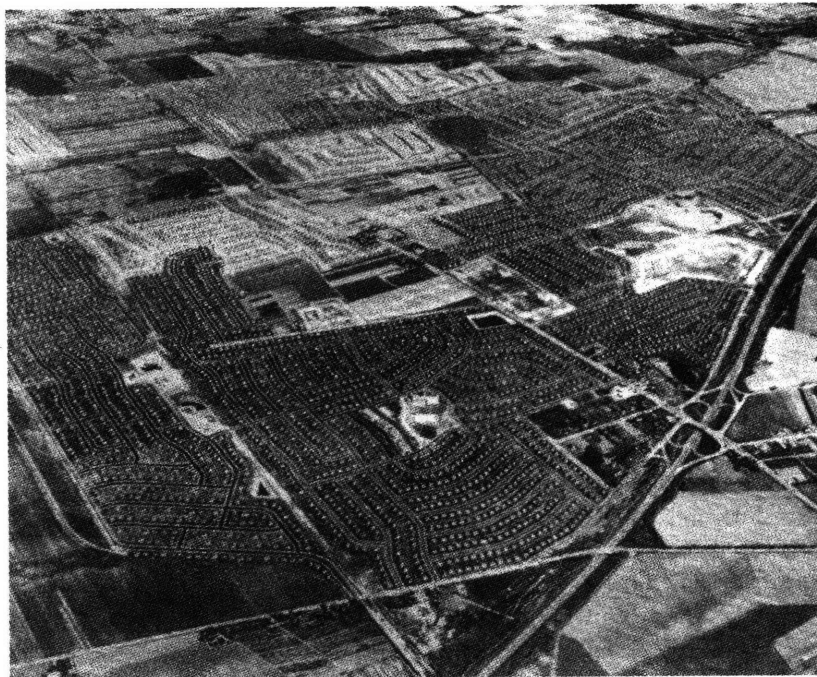


*Figure 6 - Packaged House Factory  
(Image: Herbert, p. 291)*





*Figure 7 – Packaged House Details  
(Image: Herbert, p. 250)*



*Figure 8 – Levittown Aerial  
(Image: Kelly(1), p. 152)*



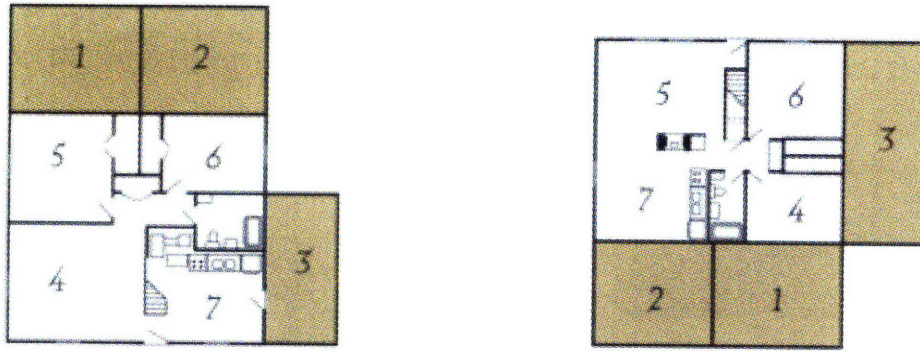
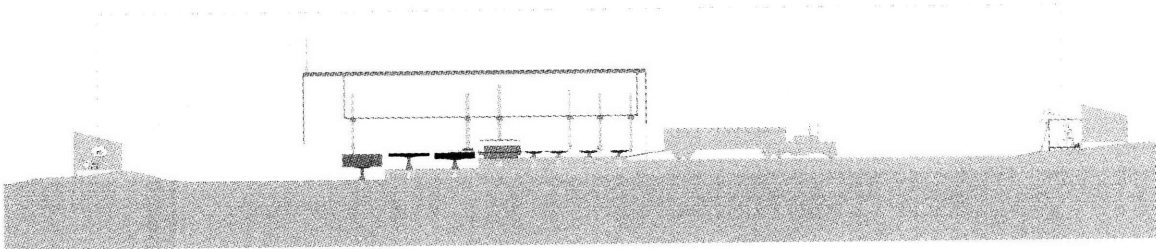


Figure 9 – Levittown Expansion Diagrams  
(Image & Drawing: Kelly(2), p. 29)

## PROPOSAL

As an alternative to the top-down approach of the Federal Housing Act, the Lustron House, and the Packaged House, this thesis proposes a bottom-up strategy for innovation in single-family housing. The proposal begins with a problem-impetus: Design a novel system for single-family housing that returns foreclosed persons as quickly as possible to homeownership and the realization of their ideal dwelling. The selection of this particular client group is important because the constraints which follow force the solution away from the in-place top-down structures that drive the housing industry<sup>54</sup> and are at the root of its fallacies: Due to the credit status of the proposed foreclosed inhabitants, the problem disallows expenditures on housing that would typically require the aid of a mortgage/home-equity style loan. Therefore, the above stated problem requires the development of the home over time and in small increments falling within the available liquid capital of the inhabitant(s).<sup>55</sup> Subsequently, as such small scale structural expansions typically fall below the economically valid scope for a hired designer or builder, both the design and assembly labor of the proposed solution must be completed by the homeowner(s) themselves.<sup>56</sup> Thus, within the constraints of the determined problem-impetus is a housing system that begins with a very minimal shelter, purchased by a foreclosed ex-homeowner without the aid of a mortgage, and subsequently added-to in small, inexpensive expansions which are themselves designed and assembled by the homeowners.



*Image 10 – Proposed System Schematic  
(Design-Fabricate-Assemble)*

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<sup>54</sup> Berhardt, p.6

<sup>55</sup> Foreclosure almost always drastically reduces the market-perceived “credit worthiness” of the foreclosed persons, tending to preclude the possibility of obtaining future loans.

<sup>56</sup> Not only is this necessary, it also would result in dramatic, initial cost savings for each addition. In single-family residential construction, labor costs typically account for a very large percentage of total building costs.

## **Starter Home**

The proposal begins with a very basic “Starter Home” design, drawing inspiration from two of the most successful precedents in low-cost, single-family housing: Levittown and the “manufactured home”.

The design-goal of this Starter Home was the following: to design a minimal but respectable home that could allow the victims of foreclosure to return as quickly as possible to homeownership but that would also support future expansion by the homeowners themselves.

While the possibility for homebuyer customization of their Starter Home was considered,<sup>57</sup> it was decided that expediency was perhaps the most important variable at the early stages of this system. The “manufactured home” paradigm, whereby a retail setting and an amenable regulatory environment<sup>58</sup> greatly expedites the process of ownership, was selected. Drawing from the success of Levittown, (re)creating homeownership for victims of foreclosure, to whom homeownership would not typically be possible, would be the first step in reversing the psychological trauma brought about by the mortgage crises.

## **Design Tools**

After the purchase and placement on site (to be discussed towards the end of this document) of the Starter Home, the new homeowner is free to add to their home, over time, using a custom computer software tool to design their expansions. The proposed software solution would not only provide functions that aid the homeowner to design and visualize possible additions, but also provide the translation between the design and the required machine “language”<sup>59</sup> used in the fabrication of the required addition

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<sup>57</sup> And design tool allowing the simple, “push and pull” of interior partitions was design and digitally prototyped, but was later discarded.

<sup>58</sup> Mobile Homes are subject not to State or Local Building Codes, but rather to the *Mobile Home Construction and Safety Standards Act*, known as the HUD code, developed by the US Department for Housing and Urban Development in 1976. This is extremely important to the development of an factory-produced housing system because it precludes the need to comply with local building codes, which vary from state to state and can be mutually exclusive for certain codes. Without the creation of the HUD code, factory-produced houses would need to comply with different codes based on where they will be sited. Such an inefficiency would almost preclude interstate manufactured housing companies. (Wallis, p. 214)

Conceptually most important is that the HUD code is *performance-based* rather than based on traditional specification standards. Thus, under the HUD code, manufactured housing is allowed to employ innovative assembly systems given that it perform in an equal or superior manner to typical construction techniques. (Wallis, p. 215)

<sup>59</sup> Often called “machine language,” or, more specifically Numerical Control (NC) language. Schodek, p. 13.

components. This combination of design tools with embedded fabrication logic<sup>60</sup> is necessary if the design and assembly of expansions to the home is done in the complete absence of design and construction professionals, as required by the problem-impetus of the thesis.

## **Fabrication System**

In current praxis, the construction costs of single-family homes are severely dominated by labor costs. Thus, one step in making economically feasible the spatial expansion of a home – without going beyond the reasonable price-point at which costs would require a home equity-style loan – is to reduce as much as possible the need for hired labor not only on-site but also in-factory. Therefore, this thesis proposes a completely automated factory production schema for the mass customization<sup>61</sup> of parts required for the individual, homeowner-designed additions. Such production processes, typically labeled “Computer Numerically Controlled,” or CNC, require the computer input of “instructions,” or “code,”<sup>62</sup> that various automated fabrication tools are able to follow for the production of parts.<sup>63</sup> Further, as all assembly of these parts, which are delivered to the site, is done on-site and by the homeowner, all parts must be cut to absolute accuracy and precision so as to prevent the need for “post-production”<sup>64</sup> on-site and to aid in the direction of the assembler by virtue of precise-fit assembly.<sup>65</sup>

## **Assembly System**

As required by the problem-impetus of the thesis, all assembly of the parts comprising the homeowner-designed expansions to the Starter Home is done by the actual homeowner(s). This therefore requires a very clear assembly logic<sup>66</sup> and simple assembly processes,

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<sup>60</sup> See Sass, Lawrence, “Wood Frame Grammar: CAD Scripting a Wood Frame House,”

<sup>61</sup> To be discussed below.

<sup>62</sup> Also called “machine language.” (Schodek, p. 13)

<sup>63</sup> Loukissas, p. 178 and Schodek, p. 13 (See Schodek, pp. 13-14, for a more detailed introduction to CAD/CAM.)

<sup>64</sup> Any process that alters the shape of the factory-produced part *after* it leaves the factory.

<sup>65</sup> See Sass, Lawrence, “Wood Frame Grammar: CAD Scripting a Wood Frame House.”

<sup>66</sup> See Sass, Lawrence, “Wood Frame Grammar: CAD Scripting a Wood Frame House,” for an example of an innovative approach to computationally rationalized assembly logic.

as well as highly precise and accurate fabrication of the required parts mentioned above.<sup>67</sup> Each part must arrive to the site pre-labeled with its part number and those of each matching part at its various joints.<sup>68</sup> Moreover, all drill-holes for fasteners must be pre-drilled to allow for the easy fastening of parts. The technical specifics of the assembly system, including material types and joining details, will be discussed further below.

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Also, for a detailed, scientific look at the theory and practice of designing assembly logics, see Whitney, Daniel E., *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*, Oxford University Press, New York, 2004.

<sup>67</sup> See Sass, Lawrence, "Wood Frame Grammar: CAD Scripting a Wood Frame House."

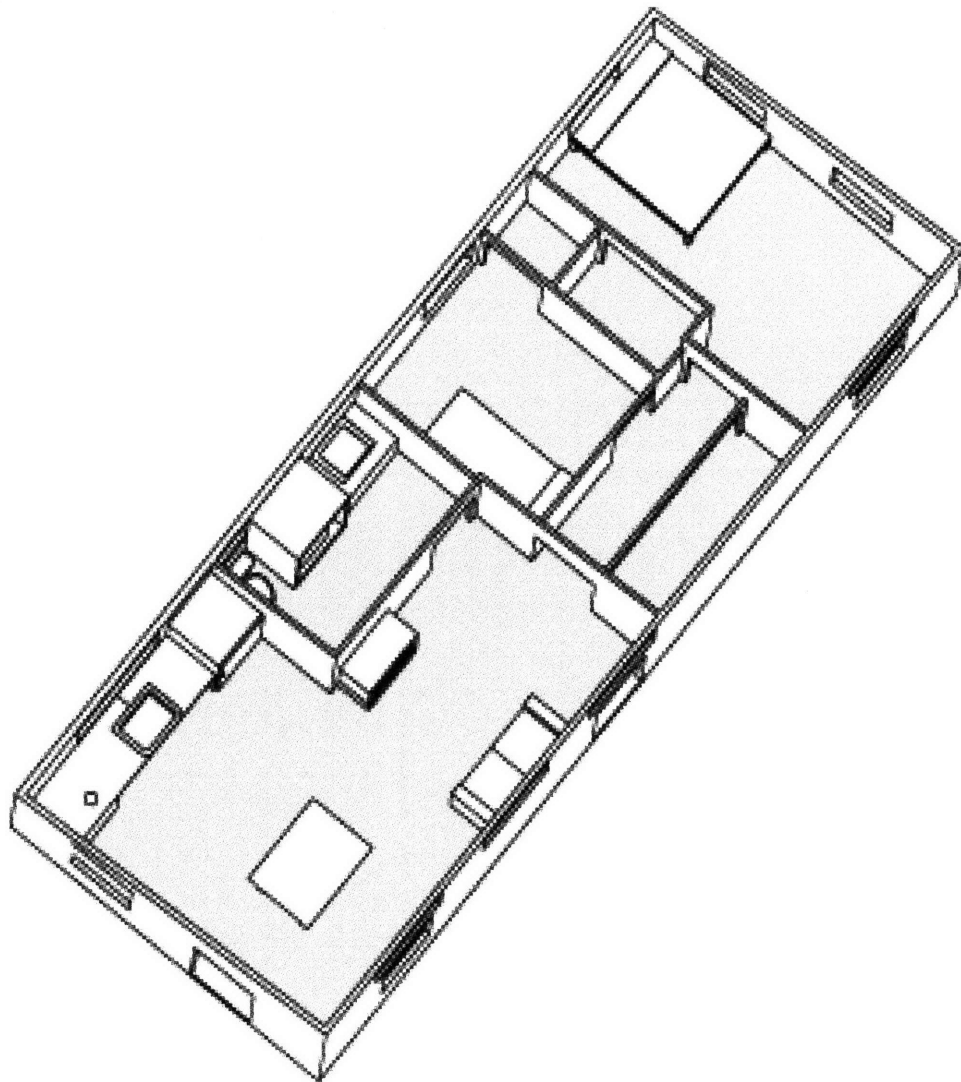
<sup>68</sup> See Sass, Lawrence, "Wood Frame Grammar: CAD Scripting a Wood Frame House."

## STARTER HOME

The design for the Starter Home (*Figure 11*) consists of a two bedroom, one bathroom minimal dwelling space for a single family and is inspired by the ultra-efficient layouts of the contemporary mobile home.

The envelope of the starter home is a basic rectangle, 39 feet long by 15.5 feet wide, sized to the legal regulations with regards to the maximum dimensions for cargo transported via interstate highways. This constraint is necessary to maintain absolute minimum costs for the Starter Home by ensuring the feasibility of in-factory mass-production for subsequent minimal cost delivery to the site. Of the two lengthwise external walls, one is a designated "wet wall," 50% thicker than the other exterior walls and containing in-wall plumbing conduits and plumbing fixtures for the kitchen and bath, which are both located along the wet wall. Plumbing conduits run the entire length of the "wet wall" to allow for "plumbed" expansions to the home off any point along its length.

The 605 square foot design is separated lengthwise into a "sleeping" and a "living" space by a bathroom that is shared by both areas. The "living" space is an open plan consisting of the kitchen and spaces for eating and recreation (e.g. watching television); and, the "sleeping" half consists of a larger, "master" bedroom, a secondary bedroom, and a storage closet.



*Figure 11 – Starter Home Axonometric*

## **DESIGN TOOLS**

### **Commercially Available Software Tools**

#### **Professional Software Design Tools**

Various types of computational design tools currently exist in software format for use by professional architectural designers. The following non-exhaustive list, in order of chronological assimilation into the field,<sup>69</sup> gives a brief overview of these tools:

#### **Computer Aided Design**

Computational tools for the facilitation of the design process of various artifacts have existed since the 1960's with the advent of the first Computer Aided Design (CAD) softwares.<sup>70</sup> In architecture, these tools were used primarily as a replacement for the drafting boards and t-squares of the designer, and, in fact, were often labeled "Computer Aided Design and Drafting" (CADD)<sup>71</sup> within the field.<sup>72</sup> CAD software<sup>73</sup> used to draw and edit designs for subsequent printing into traditional "Construction Documents" (CDs), is now common in most architecture offices in the United States.<sup>74</sup>

#### **3D Surface Modeling (NURBS)**

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<sup>69</sup> See Schodek, pp. 5-13, for a partial discussion on this chronology.

<sup>70</sup> Ivan Sutherland developed the first "interactive computer-aided design" system, "Sketchpad" in his 1963 Ph.D. dissertation at MIT. (Eastman, p. 35)

<sup>71</sup> This is analogous to the early, unsophisticated designations of automobiles as "horseless carriages." (Eastman, p. 71)

<sup>72</sup> Charles Eastman (*Building Product Models*) explains, "the easiest way to utilize a new technology is to use it to replace existing manual tasks. The framework and goals of the task are well understood and only the task methods need to be revised. Both the marketing staff of CAD companies and the early users recognized CAD's potential in production drafting and the systems evolved to better respond to this particular task [rather than the more advanced uses already developed]. From this rationale, based both in terms of how firms could effectively utilize this new tool and how CAD companies could market them, initial, crude systems were refined to support electronic drafting." (Eastman, p. 71)

<sup>73</sup> Commercially popular examples include: AutoCAD, VectorWorks, and Microstation.

<sup>74</sup> Schodek, p. 5



NURBS digital surface modeling tools allow for the design and visualization of complex, three-dimensional forms.<sup>75</sup> Such tools enable designers to represent their designs by curves (which need not be “curved,” *per se*) and the interpolated surfaces between them.<sup>76</sup> Due to approximations involved in the generation of the complex surfaces that comprise these three-dimensional “digital models,” Non-Uniform Rationalized B-Spline (NURBS) surface models are typically limited to on-screen representational functions and the creation of scaled prototypes (via digital rapid prototyping<sup>77</sup> techniques) for visualization.<sup>78</sup> In the architecture field, surface modeling has been used primarily for the creation of two-dimensional images that are created by “rendering” (simulating the effect of light on surfaces of certain material properties)<sup>79</sup> the NURBS model, however some architecture firms have begun to use rapid prototyping as well.<sup>80</sup>

### **Building Information Modeling (BIM)**

Although only beginning to gain salience within the mainstream architectural profession, the concept and development of Building Information Modeling (BIM) dates to the very earliest years of CAD itself.<sup>81</sup> While BIM

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<sup>75</sup> Indeed, many CAD systems still used by architects make it “extremely difficult to model designs that involved highly complex geometrical surfaces that [are] not easily described as parts of circles or other common shapes. With time the capabilities of these systems [have] improved dramatically, but their fundamental role as representation and documentation tools largely remain.” (Schodek, p. 5)

<sup>76</sup> For example, the windshield of a car would be “modeled” in the software by drawing the curve of its bottom edge and, above it, the curve of its top edge, and “lofting” (creating an interpolated surface) that connect the two with a smooth surface (the modeled windshield) that satisfies the two boundary conditions (its bottom and top edges are in the form of the first and second curve, respectively). This process is also described in Schodek, p. 6. And, for a detailed introduction to the mathematic principals of NURBS geometry, see Kolarevic, pp. 15-16.

<sup>77</sup> For a detailed introduction to *rapid prototyping* techniques, see Kolarevic, pp. 36-37. Also see Schodek, p. 6 and Hanna, p. 80.

<sup>78</sup> Schodek, p. 6 Also, Marsha Kelmans, in her article entitled “Bahá’I Temple: Temple of Light,” describes the use of Maya, a NURBS modeling software, uniquely for “formal exploration” and the creation of a rapid prototyped model. Beyond these early formal studies, the need to utilize a more advanced modeling software (here, CATIA) arose. This software “like CAD is extremely precise.” (Kelmans, p. 37)

<sup>79</sup> Eastman, p. 71

<sup>80</sup> For a case study, see Kelmans, and, in particular, p. 37)

<sup>81</sup> “In the early days of architectural CAD, however, a few systems evolved from assumptions quite different from those associated with [non-parametric] geometric

software typically includes three-dimensional representation tools (for use both during the design process and for rendering into presentation images), the primary benefit afforded by this computational tool is the linking of drawings to each other and to necessary non-graphical information<sup>82</sup> (such as “schedules,” or tables of text conveying the desired materials and component types to be used in the construction of the building).<sup>83</sup> Thus, the digital model is said to be embedded with “building information.” If recent trends continue, BIM tools<sup>84</sup> will soon replace simply CAD software in most architecture offices in the United States.<sup>85</sup>

## Parametric Design

Parametric design modeling software is gradually appearing in a very limited number of architecture firms throughout the United States. (*Figure 14*) Parametric means that logical relationships between geometrical elements are established during the design process and represent the “design intent” of the designer.<sup>86</sup> In addition to establishing relationships between geometrical elements (sometimes called “associative geometry”<sup>87</sup>), parametric software tools also allow the designer to relate the geometry of their design to “global parameters,” values or value-generating functions that “drive” or control certain aspects of the design from a top-down

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editors,” Charles Eastman (*Building Product Models*) explains. “That all the separate computational tools needed to design and build some facility should be integrated around a central representation of a building is not a new idea. In the mid-1970s, a number of independent efforts were made to develop integrated systems, based on a single building model supporting a suite of applications[...] These efforts each defined a single, coherent representation of a building around which all applications should be built.” (Eastman, p. 47)

<sup>82</sup> Charles Eastman explains: “Another view of CAD is that geometry is only one of many attributes involved in the representation of a product. This view takes the position that representing a product as geometry alone is very incomplete. To the basic representation of geometry, it adds other properties, such as material and performance properties[...] Material and performance properties of objects are defines as *attributes*, represented as text, numbers or compositions of simple values (such as RGB color values).” (Eastman, p. 46)

<sup>83</sup> See Johnson, p. 230-231 for a good introduction to Building Information Modeling (BIM).

<sup>84</sup> An custom adaptation of NURBS modeling software into a BIM system is described in Harfmon, p. 224-226

<sup>85</sup> Bernstein, p. 10

<sup>86</sup> Kolarevic, p. 13 & Schodek, p. 9-10

<sup>87</sup> Kolarevic, p. 17

point of view.<sup>88</sup> Such “global control” is useful in allowing the design to be quickly changed at any point in the design process without the need to create a new digital model, as well as allow for multiple iterations of the same design.<sup>89</sup> While BIM software allows for the embedding of information into the digital model, parametric software tools empower the designer to use this information to drive and constrain the design to any type of data that can be mathematically represented.<sup>90</sup> Thus, a parametric model is said to be “constrained” to the design intent or logic of the particular design,<sup>91</sup> which can be composed of information relating to, for example, site, budget, fabrication constraints, etc.<sup>92</sup>

### **Consumer Software Design Tools**

The above described tools, due to their high level of user control and thus complexity, are typically limited in their usage by professionals in the design field.<sup>93</sup> Recently, however, more and more software applications have become available to the non-professional for the self-design of their home. While these tools are far less complex and feature much more intuitive interfaces, they are limited in both the degree of flexibility they allow or the actual, practical use of the (typically graphical) information created by the user of the software. In short, consumer software design tools, in their present level of development, are insufficiently sophisticated for design outside of the *status quo* and/or for the direct translation of these designs into information (drawings or otherwise) that can be used to construct the designs created using them.

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<sup>88</sup> Aish, p. 336, Hanna, p. 79, and Schodek, pp. 9-11

<sup>89</sup> Hanna, p. 79 and Schodek, p. 9-11

<sup>90</sup> Bechtold (“Digital Design and Fabrication of Surface Structures”) describes the use of data relating to structural analysis (performed using Computational Finite Element Analysis or FEA) as input as a design constraint/driver for a parametric model. Johnson, Von Buelow, and Tripeny (“Linking Analysis and Architectural Data”) provide a good case-study explanation for the difficulty of deriving meaningful downstream data from BIM models. (Johnson, p. 230-243)

<sup>91</sup> Kolarevik, p. 14

<sup>92</sup> “Buildings and projects in general are conceived within a complex web of planning and building regulations (which are by no means fixed constructs), various technical constraints, environmental conditions, such as sun, wind, precipitation, etc., and are meant to operate in a highly dynamic socio-economic and political context, which has its own “force fields” such as, for instance, numerous interest groups. Some of these influences could be quantified and their changes modeled in order to simulate, past, and predict present and future, impact.” (Kolarevic, p. 21) Also see Schodek, p. 6 & 9-11.

<sup>93</sup> Schodek, p. 6

## **Builder-Proprietary Design Tools**

The most facile computational method for do-it-yourself design is the Builder-Proprietary Design Tool. These typically exist on the websites<sup>94</sup> of established homebuilding companies and allow the potential homebuyer to “customize” their home design. Typically, the design process begins with a series of questions relating to the desired home design (e.g. square footage, basic “style,” number of bedrooms, etc.) then presents the potential homebuyer with one or more designs from the builder’s stock catalogue of home designs fulfilling the design criteria of the potential homebuyer as established by their responses to the questions. While severely limited in design flexibility (indeed, the appropriate term here would be “design choice”), this method of consumer software design tools is very efficient in that it guarantees the “tried-and-true-ness” of the design and is able to tap into the extant production system of the builder.

## **“3D Home Architect”-Style Software**

One of the first non-builder linked consumer-grade home design software packages was called “3D Home Architect,”<sup>95</sup> and many others have followed. These tools are most closely related to BIM software in that it provides a two-dimensional design interface that allows for the visualization of the design in simulated three-dimensions and allows for the linking of design geometry to non-graphical information relating to materials, component types, and (sometimes) construction. However, these consumer software tools are limited as compared to their professional counterparts in terms of design flexibility (they typically direct the non-professional user towards very standard, traditional design forms), level of detail, and production of documents useable in the construction of the design.

## **SketchUp**

The latest consumer-friendly design software is Google Inc.’s “SketchUp”.<sup>96</sup> As its name suggests, this tool allows for

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<sup>94</sup> For example, [www.designyourownhome.com](http://www.designyourownhome.com), from Toll Brothers homebuilders.

<sup>95</sup> Copyright 1999-2007 3D Home Architect, [www.3dhaonline.com](http://www.3dhaonline.com)

<sup>96</sup> Recently, professional PLM software company Dassault Systemes introduced, in partnership with Microsoft Corp., an alternative to Google’s SketchUp called “3DVIA.” It operates in a fashion very similar to the former.

the digital “sketching” of a design in three-dimensions. Unlike the above two consumer-grade software tools, “SketchUp” does not presume any particular formal constraints or standards, nor any particular construction system, but, rather, allows for the creation of designs in three-dimensions by adding and subtracting various primitive and extruded three-dimensional geometries to and from each other. Used even by some professional designers, “SketchUp” is the most flexible software-based design tool for the consumer, however this flexibility comes at the price of ease of use: the creation of even a modicum of detail required for architectural design requires an understanding of three-dimensional digital modeling that goes beyond that of most nonprofessionals. Further, the lack of embedded construction/assembly logic in the software disallows its use for anything beyond early conceptual design and three-dimensional representation.<sup>97</sup>

### ***Design-It-Yourself Software Tool***

At present, no software tool exists or is commercially available that could allow for the practical do-it-yourself design of additions for automated fabrication, as is required by the thesis proposal.<sup>98</sup> To a large extent, however, the computational technology or sophistication presently available is, in fact, sufficient to make this possible. Indeed, parametric software such as CATIA<sup>99</sup> has been used by architecture firms to create very innovative buildings wherefore the parts used in their assemblies are CNC fabricated directly from the three-dimensional parametric model.<sup>100</sup> What is missing, however, is an *interface for design* that would be sufficiently intuitive to be accessible to the homeowner.<sup>101</sup>

To propose a recipe from scratch for such a software and interface falls outside of the scope of this thesis. Alternatively, this proposal seeks to demonstrate the *feasibility* of creating such a

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<sup>97</sup> See Schodek, p. 12, for a general description of “conceptual design” software limitations.

<sup>98</sup> This task, rethought for the consumer, mirrors Charles Eastman’s assessment in the late 1990’s: “The challenge before us is *to develop an electronic representation of a building, in a form capable of supporting all major activities throughout the building lifecycle.*” (Eastman, p. 72) (italics Eastman’s)

<sup>99</sup> Product Lifecycle Management (PLM) software developed by Dassault Systèmes. The acronym stands for “Computer Aided Three-Dimensional Interactive Application.” It was developed for French aerospace industry. (Kolarevic, p., 31)

<sup>100</sup> Example described in Kelmans, p. 37. For a general introduction, see Schodek, pp. 6-13.

<sup>101</sup> Parametric design software packages “have been developed to support *design development* activities. They are not intuitive “design conceptualization” tools. (Schodek, p. 6)

software tool, in particular with regard to debunking certain commonly held beliefs about the inherent limitations of the technology which, if not lifted, would make such a tool impossible. Therefore, a large portion of this thesis was dedicated to creating “computational mockups” of necessary though believed impossible functions of such a computational design tool, similar to the manner in which one might mock-up a difficult detail of an assembly to demonstrate its feasibility and how it might be constructed.

The following sections will describe and explain these functions, how they can be created, and why they are important or necessary for a feasible consumer design tool for do-it-yourself design-build of expansions to the Starter Home. Please note that while all of the created computational mockups were created on top of Dassault Systèmes CATIA v5 r16, very similar principles would apply to any sophisticated parametric software platform onto which one might build these tools.

Building these tools atop of an existing parametric software framework afforded multiple advantages within the context of this thesis. First, the software already contains the required three-dimensional modeling and visualization functions necessary, rendering unnecessary the very long and tedious process of “coding” such computational functions from scratch. Further, unlike NURBS modeling software, which tends to approximate derived geometry based on software specific mathematical algorithms for surface geometry,<sup>102</sup> “solid” modeling software,<sup>103</sup> such as CATIA, often use more precise mathematical functions<sup>104</sup> which are standard across multiple software platforms.<sup>105</sup> This level of precision is necessary if the software is to be used not only for designing the form of the additions, but also for producing consistent “code” – via embedded Computer Aided Manufacturing (CAM) functions<sup>106</sup> – that tells the automated fabrication machines<sup>107</sup> how to produce the necessary parts<sup>108</sup> to a high level of precision and to ascertain that all joined

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<sup>102</sup> While this specificity of proprietary algorithms for surface definition can create inconsistencies, Charles Eastman (*Building Product Models*) provides insight in explaining that translation into “neutral file formats,” such as “IGES,” does not solve the problem, as such conversions “may result in approximations and numerical problems.” (Eastman, p. 100)

<sup>103</sup> For a detailed, scientific explanation of the geometric and mathematical logics behind digital solid modeling, see Eastman, pp. 179-203.

<sup>104</sup> Schodek, p. 9

<sup>105</sup> Schodek, p. 6

<sup>106</sup> “Manufacturing applications packages (such as CATIA) form a key building block in the CAD/CAM system by providing a software link between the computer-aided design model and the actual numerically controlled (NC) production equipment. (Schodek, p. 13)

<sup>107</sup> Schodek, p. 4 (Example found in Bechthold, p. 92)

<sup>108</sup> For a detailed look into the roll of CAD/CAM integration, see Kolarevic, pp. 58-62.

parts will have a precise fit.<sup>109</sup> The “design logic” methodology of parametric software was also useful in facilitating the creation of the thesis design tools. While it is presumed that such a more sophisticated design computing methodology is not suitable to the lay user, creating a “behind-the-scenes” framework of constraints and design-drivers using parametric software is a useful simulation to a from-scratch design-it-yourself interface that, while remaining sufficiently flexible, ought to constrain the design possibilities within certain pre-determined logical boundaries. Finally, most high-end parametric software packages allow the user to create custom “scripts” or “macros” – computer language that tells the software what to do without the need for user input such as clicking or typing.<sup>110</sup>

*CAD systems that provide an application development platform allow implementation of some powerful and useful applications. While a geometry editor carries no special knowledge beyond geometry about a product, the extended applications built on top of them are able to incorporate design or construction rules, checks about legal compositions and other product information of central importance to the product field. For a given type of produce design, these capabilities can be immensely useful and begin to realize the image of a CAD system as a design or engineering assistant.*

In the context of this thesis, the ability to do so was essential to the “customization” of the software (CATIA) as a do-it-yourself design-build software tool for homeowner-designed expansions to existing homes.

## **Site Simulator**

### **A word about site ethos...**

Architectural production is not a closed system – many factors external to the actual architectural artifact (the house)<sup>111</sup> play a role in driving and constraining its design. The extant site topography is one such factor.

Two opposing ethos can be held towards the role of site in single-family design: (1) that the house *must* conform to the

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<sup>109</sup> “Not all[...]digital environments, however, are equally useful in supporting connections to subsequent manufacturing and assembly processes. An image that appears strikingly three-dimensional and photo-realistic does not mean that the underlying computer model can be used directly within a computer-aided manufacturing environment.” (Schodek, p. 4) Also see Schodek, p. 6, for an introduction to solid modeling and p. 8 for a detailed explanation of the need for numerical/geometrical precision in the design process.

<sup>110</sup> Eastman, pp. 46-47 (underline mine)

<sup>111</sup> In this case, the single-family home



topographical conditions of the site, therefore a site shifting in elevation will be translated into sectional shifts in the house design or (2) the single-family house is autonomous from the site and the latter can simply be made to conform to the needs of the design (a view held by most suburban housing developers and some elite architects<sup>112</sup> alike). Both for technical and design reasons, this first site ethos is taken in this thesis.

Site-ambivalence requires extensive site/foundation work that cannot be a part of a do-it-yourself system. Excavation and the construction of retaining walls needed to alter a topography to conform to an autonomous design, as well as the pouring and smoothing of large foundations, requires specialized skills and large, expensive machinery – neither of which can be a part of the proposed system.<sup>113</sup>

From a design point of view, site-specificity is one boon afforded by a mass-customized system and ought to be embraced for its ability to produce variation and context amidst a large grid of suburban plots. Rather than smooth-over the effect of site as is done in typical, Mass Production-generation of suburban sprawl, this thesis seeks to promote sectional responsiveness of the individual homes as the homeowner expands their Starter Home over time.

Therefore, it is necessary that whatever software application used by the homeowner to design their additions has knowledge of and is capable of responding to the topographical condition of the specific plot of land upon which the home rests.

### **The tool...**

The prototyped software tool (*Figure 12*) designed for this thesis receives uploaded topographical data about the specific plot of land for the home and positions the floor level datum of the Starter Home digital model (prior to the fabrication of its supporting pylons<sup>114</sup>) and each subsequent addition such that it rests just above the topography of the site. Thus, the do-it-yourself designer is compelled to acknowledge and engage their specific site during the design process.

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<sup>112</sup> Contrast Frank Lloyd Wright's site-embedded designs to the site-ambivalent work of Peter Eisenman, for example.

<sup>113</sup> See chapter on the proposed Assembly System for a detailed explanation of how this ethic is proposed to manifest.

<sup>114</sup> See chapter on the proposed Assembly System for a detailed explanation of this requirement.



## **Technical Explanation**

The process for determining the proper sectional height of the Starter Home and each subsequent addition is one of sampling the site and ascertaining that the ground plane datum of the architecture will lie just above the site without intersecting it. A ground plane that intersects any topographical shift in the site will result in an addition, for example, that cannot be built without excavation and the pouring of a foundation.

Regardless of whether the tool is used for designing the position of the Starter Home on the site or for supporting the design process of each subsequent addition, the tool performs essentially the same functions. The ground plane of the architecture in this proposal remains horizontal at all times, however the topography of the ground below the architecture may not be so. To determine the highest point of the ground below the addition (and therefore the minimum height of the ground plane datum), the area of land below the design in question (Starter Home or addition) must be delineated. This is done by “projecting”<sup>115</sup> the in-process footprint of the new design onto the digital simulation of the site. This projection will mark the limits of the topographical condition to be analyzed in the computational determination of the ground plane datum.

Within that boundary, sample points are “populated” at equal intervals positioned on the simulated topography. The height of these sample points can be compared, with the highest one indicating the maximum height of the topography below the design and therefore the minimum height of the ground plane datum. From this height a tolerance is added and the datum plane from which the design begins in section is determined. As the position and footprint of the design changes, this datum plane automatically updates, along with the sectional condition of the design.

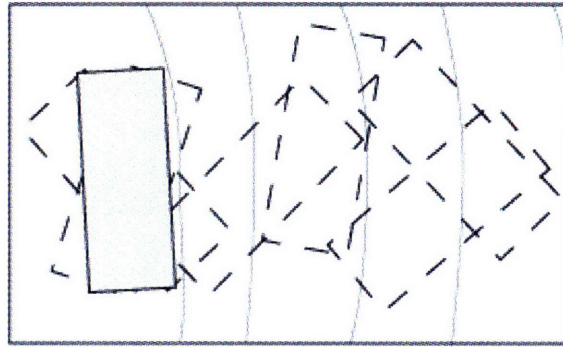
## **Implications**

Site is one of the major external factors that has served to greatly reduce the ability to pre-rationalize and therefore industrialize the production of single-family

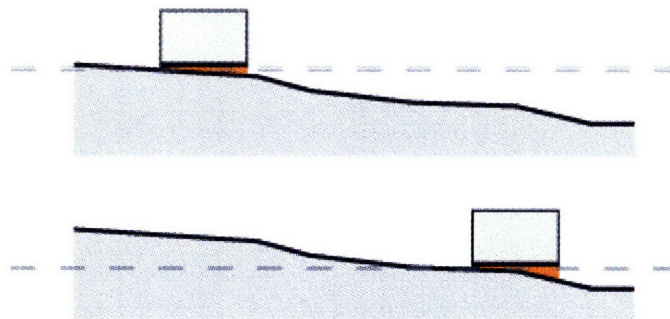
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<sup>115</sup> Vertical lines at sampled points on the two-dimensional footprint are digitally drawn. The points where these vertical lines intersect the simulated topography are connected to form the “projected” footprint on the surface.

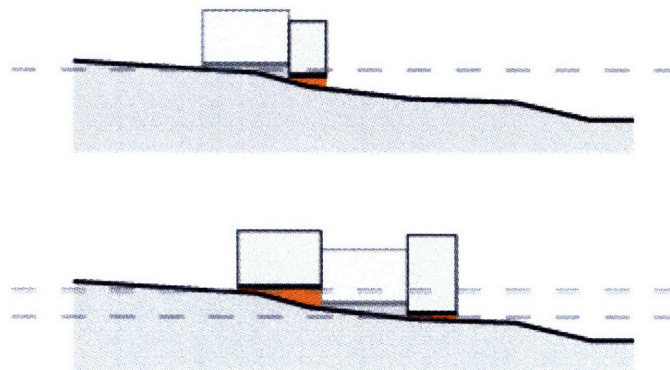
housing. Without knowledge of site and the ability to respond to its topography during the design process, the assembly process of a house always falls back into "construction" – the on-site, piece-by-piece measuring, cutting, and fitting of contingency parts (buffers) in response to unforeseen conditions. Within this thesis, such professional construction techniques are not possible; on-site, the completion of the house must be a process of assembly, not post-production, meaning that all components shipped to the homeowner must fit into their neighbors and onto the site with absolute precision. Otherwise, a large percentage of the cost savings for the home is lost and, by the assumed constraints of this thesis, the proposed system fails. A tool allowing the accurate simulation of the topography of the specific site during the design process is crucial for a do-it-yourself design-build system.



Computational tool allows the design-it-yourselfer to select the position and orientation of their starter home on their selected specific site.



Computational tool automatically determines the floorplate height of the starter home based on the local topography below the selected position and orientation of the starter home on the site.



Computational tool automatically determines the floorplate height of the each added addition based on the local topography below the selected position and orientation of the starter home on the site.

*Figure 12 -Site Simulator Explanatory Diagram*

## **Unfolding Walls – Designing the Footprint for the Addition**

The primary design tool created for this thesis was called the “Unfolding Walls” tool. (*Figure 13*) The design process using this tool is as follows: In either plan or axonometric view, the user drags two points along the exterior envelope of a three-dimensional model of their home at the time of design. These two points, in plan, represent the boundary extents where the new addition will meet the extant home. From this intersection in plan, the user “unfolds” new walls representing the desired footprint of the addition out of the extant home. The user is free to drag around the corner points of these walls to edit their design, to unfold more walls by “pulling” (dragging) on a wall adjacent to the relative position where they would like to add another wall, or re-fold walls that have been mistakenly unfolded. Taking advantage of relational geometry – where the addition is automatically updated to match the designed footprint – the design process of the plan becomes an intuitive process of “pushing and pulling” the design into the desired footprint for the addition.

### **Technical Explanation**

A major obstacle in achieving such facile manipulation of the footprint while maintaining a high degree of flexibility is that these two traits are thought to be computationally mutually exclusion. In the above discussed software precedence, for example, each piece of software can either be said to be very flexible in terms of allowing a large degree of design freedom or to feature a very intuitive and simple interface for design. This is because simplicity in interface is often achieved by drastically limiting the possible outcomes of a design by somehow constraining the design behind-the-scenes. The *builder-proprietary design customization software*, for example, is very easy to use because one is only to answer a given set of multiple-choice questions and a set designs is automatically selected, by the software, which meets the user’s criteria as per their responses to the questions. NURBS modeling software, on the other hand, can be used to create almost any design, however doing so requires quite a bit of pre-rationalization that typically falls outside of the reasonable skill-set of the non-professional.

To achieve both desired traits, it is necessary to force the software to “switch hats,” so to speak, in real time, between tightly constraining the design (and

therefore simplifying the interface) and allowing a high degree of flexibility. The ability to “push and pull” on the footprint until the desired design is achieved is possible by fixing (locking-in/“constraining”) the number of walls, constraining or fixing them together, and fixing them to the two boundary points where the in-process addition will intersect the extant home. The effect is analogous to a set number of elastic bands (the walls), each knotted to its neighbor, and the two bands at the ends connected to fixed pegs (the points where then new walls will intersect the existing ones). With these characteristics fixed, the “solution set” is sufficiently limited to allow the user to freely drag corners of their footprint design around the screen while maintaining the logical requirement that the walls must connect to one another and that the addition design must connect to the house.

Off-the-shelf parametric software is perfectly suited for creating such constrained conditions, and the process is typically as follows: the designer draws a series of connected lines (one for each wall), then places a “constraint” on the open endpoint of the line at each end of the chain “fixing” that point to the points at which the walls are to connect to the extant home geometry and which are fixed to the boundary of the existing house. Once this is done, the home user (to whom the software arrives with this already completed and “locked” behind the scenes) would be free to change the position of the two boundary points along the extant house geometry and the corner points between the walls until the desired addition footprint is achieved.

However “elastic” the length of these footprint walls are (they simply “stretch” to any length when the user “drags” their corner point), the design is nonetheless inflexible in that the total number of walls of the design must be pre-determined. Having a fixed number of segments, the digital geometry is said to be “topologically” determined,<sup>116</sup> a necessary precondition to the above described “push and pull” parametric flexibility. In dealing with this paradox in the thesis, it was found that in order to bypass fixing the number of walls for the addition, the software must have a pre-determined number of walls far in excess of the reasonable amount walls that would be desired, but that the software would have to be “tricked” into acting as though only the desired number of walls existed in the digital model.

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<sup>116</sup> Kolarevic, p. 13



This was done by utilizing a custom “macro”<sup>117</sup> that would “constrain” or lock the two endpoints of any undesired wall segments of a pre-user-drawn chain of many walls linking the two boundary points of the addition where its walls meet those of the extant home. Thus, when the user begins designing their addition in the software, the two moveable points that define their addition’s insertion position are connected by a single wall; but, as this wall is “dragged” out from the extant home geometry, two additional footprint lines, previously nested within their endpoints which were constrained together, “unfold” from the points to allow a space to be created. The design process continues by the following: whenever the user pushes or pulls on a corner between two walls, this corner’s position (and thus that of the two adjacent walls) is adjusted accordingly; however, whenever the user pulls on one of the walls itself, a new wall is unfolded from the corner of the design’s footprint closest to where the user has “grabbed” the wall with their cursor. If the user decides that they no longer desire a previously unfolded wall, they simply drag one of its adjacent corners over to its other adjacent corner and the macro constrains the two corners together thus re-nesting/removing the wall. Only non-nested walls are taken into account by the software when displaying the design either in plan or perspective, or when generating the required “code” for the automated fabrication processes.

### Implications

The ability to combine pre-rationalization and flexibility is a crucial development towards a do-it-yourself design-build system. In the “Unfolding Walls” example, this paradoxical dualism allows for an intuitive design interface (by virtue of a pre-rationalized parametric system allowing “push and pull” design) while freeing the do-it-yourself designer to be truly creative.

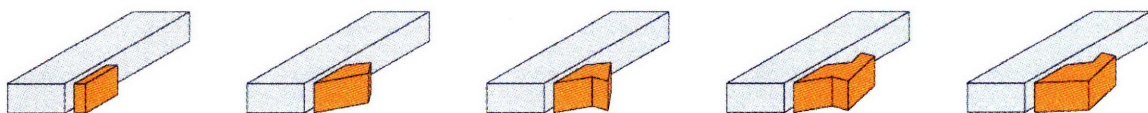


Figure 13 – Unfolding Walls Explanatory Diagram

<sup>117</sup> Defined above.

## Clay Manipulation Design Tool

Linked to the above described challenge of allowing the do-it-yourself designer uninhibited freedom to design without pre-determining the possible outcomes is the possibility that roadblocks to this freedom exist beyond the technical hurdles of the computational interface on which the homeowner is designing. The do-it-yourselfer is, indeed, not a trained designer. While certain technical skills are part of the architect's training, a large part of this education can be said to be a "releasing" of the designer's mind from preconditioned biases about what buildings *should* look like in order to free the designer to create innovative, or at least thoughtful, designs that respond to the specific situation of the design at hand. Untrained in such way, the do-it-yourself addition design-builder may be intuitionally constrained by (unconscious) biases that could prevent the cost-effective use of recourses in developing, over time, the ideal home for the specific inhabitants, as opposed to a passive recreation of generic cookie-cutter spatial typologies that achieve general suitability by wasteful overproduction of space.

If the "Unfolding Walls" tool can be qualified as enabling the homeowner to design (almost) whatever they desire for their additions over time, the following tool (*Figures 14-17*) can be considered a method of helping the homeowner, sans architect, to discover what it is that they actually desire.

Specifically, this tool is meant to supplement the "push-pull" method of design described above. The driving idea behind this tool is the possibility that, for some users, absolute direct control over their design from the beginning may be an overwhelming task, leading to a sense of anomy rather than empowerment. The goal of this tool is to allow the do-it-yourself design to manipulate their design by "pushing and pulling" not on the actual walls of their design, but rather on a volume of digital "clay" that will be translated into a feasible addition design by a prescribed computational algorithm. (*Figure 16*) By allowing the user at any point in the design process to place an almost playful intermediary between the actions of the user and its effect on their addition design, the hope is that the user will feel, once again, more liberated to experiment and empowered to design without constantly fretting over the precise dimensional details of their design from the onset. (*Figure 17*) Nonetheless, the tool is not meant to supplant the direct manipulation of the expansion design by the homeowner, but rather to serve as a starting point to thinking about their spatial options prior to delving into direct manipulation.

The tool works in the following way: At any point in the design process, the user can turn on the clay manipulation tool.

Once this is done, a translucent volume of digital clay that loosely approximates the home in its present state, including the in-process addition being designed, appears on the screen around the digital model of the house. By pushing and pulling on the digital clay, the designer is able to affect the form of their in-process addition design which attempts to “achieve” the form of the clay, in both plan and section, without going beyond pre-rationalized constraints (such as budget, proportional spreads, fabrication/assembly constraints, etc.). The user can continue to manipulate and “play” with their design in this way, or, at any point, they can return to direct manipulation of walls and wall heights in the crystallization of their design.

### **Technical Explanation**

The Clay Manipulation Design Tool combines the advantages of two separate digital modeling technologies into a novel aggregate for this thesis.

The first of these is parametric modeling, which has the advantage of maintaining a complete mathematical rationalization of the digital model in order to allow the creation of internal and external relationships and downstream data creation (such as creating “code” for automated fabrication<sup>118</sup>). Parametric modeling, because of this ability to organize data and relationships, is the primary platform on which the design tools created for this thesis are based. This powerful data management framework, however, requires a clear hierarchy of parent-to-child geometry creation; in other words, a surface must be created from an extant and fully “defined” curve which itself must be created by a set of extant and fully “defined” points. This hierarchical parent-child relationship, however, must at all times be maintained, which severely limits the flexibility of the interface.<sup>119</sup> In the above described genealogy, for example, the user would not be able to manipulate this surface itself in any significant manner because this would require an alteration of the curve used to create the surface, and thus a reversal of the hierarchy (A child, using this terminology, cannot alter its parent.). Thus, in order to manipulate the surface, the user would be limited to manipulating the points only, which would, in turn, automatically update the curve, which, again in turn,

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<sup>118</sup> As exemplified in Bechtold, p. 92

<sup>119</sup> Kelmans describes the potential for a design to become “muted by CATIA’s rationalizing effect.” (Kelmans, p. 36)



would automatically update the surface – an extremely unintuitive process. This hierarchy is particularly difficult to work around when dealing with surfaces, due to their complex mathematical definition.<sup>120</sup>

Therefore, in order to create directly manipulatable digital clay for this thesis, an alternative modeling technology needed to be employed: subdivision surfaces. This second digital modeling technology can be thought of as a patchwork quilt of flexible nylon material: while the location and size of each subdivision (patch) is arbitrary, the only rule is that the seams between these patches cannot come apart. Therefore, if one is “stretched,” those adjacent to it must also stretch slightly to accommodate this action without breaking their joining seams. If a greater level of “stretching” detail is desired, a “patch” can be automatically replaced by a “mini-quilt” of multiple patches in the same location. In this manner, the user is free to “stretch” and mold the subdivision surface directly and locally without needing to “redefine” the entire surface globally by altering its parent geometry. Digital modeling with subdivision surfaces is, in fact, extremely intuitive and closely mimics the thought process of using clay.

For this thesis, the subdivision surface used to create the digital clay volume can be visualized as a stitched quilt organized much like a deformed soccer ball to achieve a closed volume. The user simply “grabs” part of the digital clay volume wrapped loosely around the digital volume of their home and “pushes and pulls” it into a certain form while watching, in real time, the effects of their manipulations of their in-process addition design.

Nonetheless, subdivision surface technology is not a valid replacement for parametric modeling *in toto*, as it lacks the ability to organize data and allow internal and external relationships between elements, a quality which must be maintained in the digital model of the existing home and the addition in order to make possible controls for budget, assembly, etc, as well as for downstream fabrication processes. Thus, the digital clay, created using subdivision surface technology must be combined with and able to “communicate” with the parametrically modeled house and addition design. This is done with, what could be called, parametric “feelers.”

Because they are generated of two different computational logics, the two different models (“clay”

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<sup>120</sup> A further, more general, explanation of this issue can be found in Schodek, pp. 9-11.

volume and house/addition) contain no inherent "knowledge" of each other. Thus, while each geometrical object in the parametric house/addition model can "access" information about any other object in the house/addition model by virtue of their being part of the same network or "web" of data, and therefore can, if pre-rationalized to do so, can react to operations performed on other geometric objects in that model; manipulating the digital clay - even though it is represented on the same screen, in the same space, and within the same interface of the house/addition model - will have no effect on the parametric model.<sup>121</sup>

It was discovered, however, that while subdivision objects cannot affect parametric models, a parametric object can "feel" the existence of a subdivision surface at a certain position. Thus, it is possible to gather information about, for example, where a parametric object intersects a subdivision surface. In this way, a parametric model can act as a blind animal with "feelers," gathering information about its surroundings in small bits of data that are then compiled into a fairly accurate "picture" of "invisible" objects.

In order to create the parametric "feelers" in the digital model, ostensibly infinitely expanding straight curves were created at a range of angles radiating, in both plan and section, from the region where the user is adding their new addition. The extremities of the radiation coverage were determined by evaluating the existing condition and limiting the receptivity of the feelers to directions in which it would be logically possible for the addition design to extend (i.e. above grade and not back into the Starter Home), thus the parametric model is only aware of manipulations to the Digital Clay that are relevant to the goal of forming the addition being designed. Limiting the range of interaction between the two models is necessary in order to minimize the amount of simultaneous calculations required to "sense" and compile the do-it-yourself designer's manipulations and to maintain instant visual feedback of the results. Within this range, the number of "feelers" used is simply a matter of desired resolution. For example, in the tool

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<sup>121</sup> "Even though a single CAD system may support the effective development of multiple add-on applications," Charles Eastman (*Building Product Models*) notes, "it is not likely that these applications will operate together. The different applications may each rely on different definitions of the objects representing a building, different relationships among objects and different rules of how objects are composed." (Eastman, p. 47)

utilized in this thesis, it was found that placing parametric “feelers” every fifteen degrees in plan and section provided ample resolution (the user’s manipulations of the Digital Clay altered addition’s form in a comprehensible manner) without overly taxing the computing engine with unnecessary demands for precision.

The purpose of the “feelers” is to intersect the Digital Clay. Although derived in part from a non-parametric object (the subdivision surface comprising the Digital Clay), this intersection of the parametric “feeler” geometry and the Digital Clay is able to be measured in terms of its distance along the “feeler” length relative to the origin of the feeler on the in-process addition. Because the angle of each “feeler” (relative to the Starter Home) is known to the parametric model, the knowledge of both the distance and angular position of the sampled (intersection) point on the Digital Clay, that point’s precise location relative to the Starter Home is now available to the parametric model. By compiling the position of all of these points, the parametric model is thus able to “understand” the form of the Digital Clay, within the relevant region, at any given time in the design process when using the Digital Clay tool.

When the user pushes or pulls on the Digital Clay, the parametric addition model calculates a difference between the relative position of itself to the Digital Clay and alters its size and form so as to maintain – within a preset tolerance and without breaking pre-rationalized constraints (relating to budget, proportions, assembly rules, etc.) – its original relationship to the Digital Clay. In this way, the addition design is always trying to “become” the Clay, but is limited dimensionally and formally in ways the Clay is not.

One such limitation results from the addition’s being composed as walls, rather than a continuous surface like the Digital Clay. While the addition can be comprised of any number of walls, as proscribed by the user, manipulating the Digital Clay does not automatically increase the number of walls in the addition design. While an increased amount of walls would indeed augment the ability of the parametric model to approximate the form of the Digital Clay, the goal is not to *recreate* the form of the Clay, but rather to use the Clay as a liberating instigator of different forms based on previous design moves made directly by the do-it-yourself designer. However, if the resulting form of the addition design model, after the user has completed

experimenting with the Digital Clay tool, no longer requires<sup>122</sup> a previously unfolded wall, that superfluous wall will be automatically removed as though it was “re-nested” directly by the user.

Another necessary limitation to the mimesis by the addition of the Digital Clay relates to efficiency concerns relating to budget: the “Desire Realization Coefficient” (DRC). In this thesis, it was determined that, while maintenance of the creative freedom of the do-it-yourself addition designing is very important, highly nonstandard forms become extremely inefficient for very small additions. Thus, in order to remove “noise” from the user’s process of experimenting with the Digital Clay for inspiration towards new spatial typologies, the degree at which the parametric model will assume a non-standard (extreme angles and proportions) forms (the DRC) is relative to the size of the addition. Thus, if budgetary limitations allow for the addition design to achieve only fifty percent of the size “desired” by the Digital Clay, the resulting addition model will also be limited to a DRC of, say, twenty-five percent, determining the degree of angularity of the Digital Clay’s new position relative to the origin. An optimal proportion has yet to be determined within this thesis relating size of addition to angularity (off of perpendicular), however experimentation has found that the angularity of the resulting addition ought to be limited much more than its size when taking into account economic/spatial efficiencies at the small scale of the single-family residential addition.

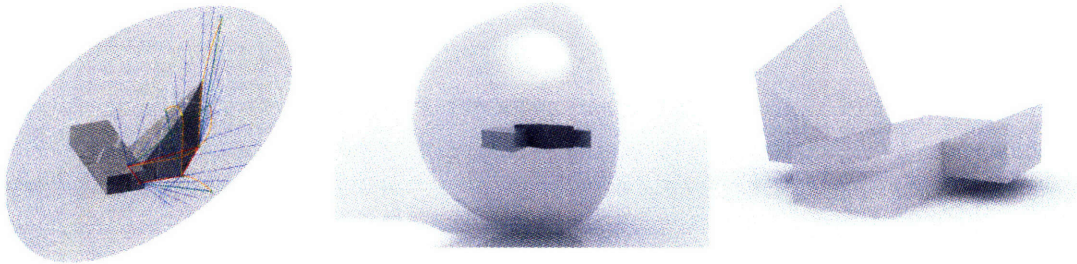
## **Implications**

The ability to “play” freely during the design process is potentially one step towards liberating the do-it-yourself designer from unfounded biases related to generalized cookie-cutter housing typologies. The goal here is not to *force* the homeowner to design non-standard, formal expansions, but rather to inspire an open mind toward what kinds of spatial and even programmatic conditions can be created that go beyond simply scaling back the standard suburban typology. It is the contention of this thesis that mass customization – or the ability for the homeowner to design what best suits their specific needs or desires for the same or lower cost

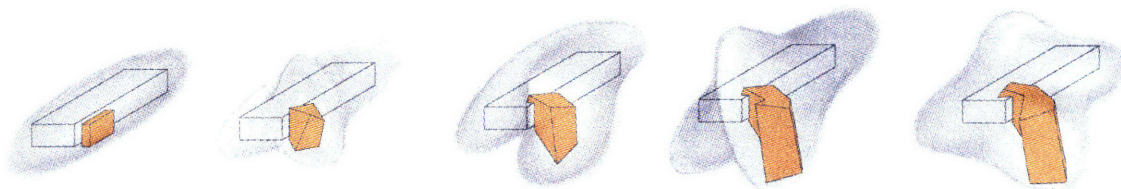
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<sup>122</sup> This would occur if the resulting wall had become less than a pre-determined minimum length, such as one foot.

than a generalized, mass produced solution – is one strategy for providing decent housing for an extremely low budget. Indeed this “efficiency by variability” is a central tenant of the economic theory of mass-customization.<sup>123</sup> However, biases created by the mass produced housing industry that have “pushed” generalized spatial typologies onto the public must first be removed from the list of constraints that hinder, here, the previously foreclosed homeowner from making wise decisions about how their needs and desires might be efficiently translated into architectural space. Liberation and creative innovation is teased out of the user by inciting almost naive “play” with proto-architectural space – Digital Clay.



*Figure 14 – Clay Manipulation Design Tool (Concept Diagram)*



*Figure 15 – Clay Manipulation Design Tool (Sequence Diagram)*

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<sup>123</sup> See Pine, *Mass Customization* for an in-depth introduction on the topic.

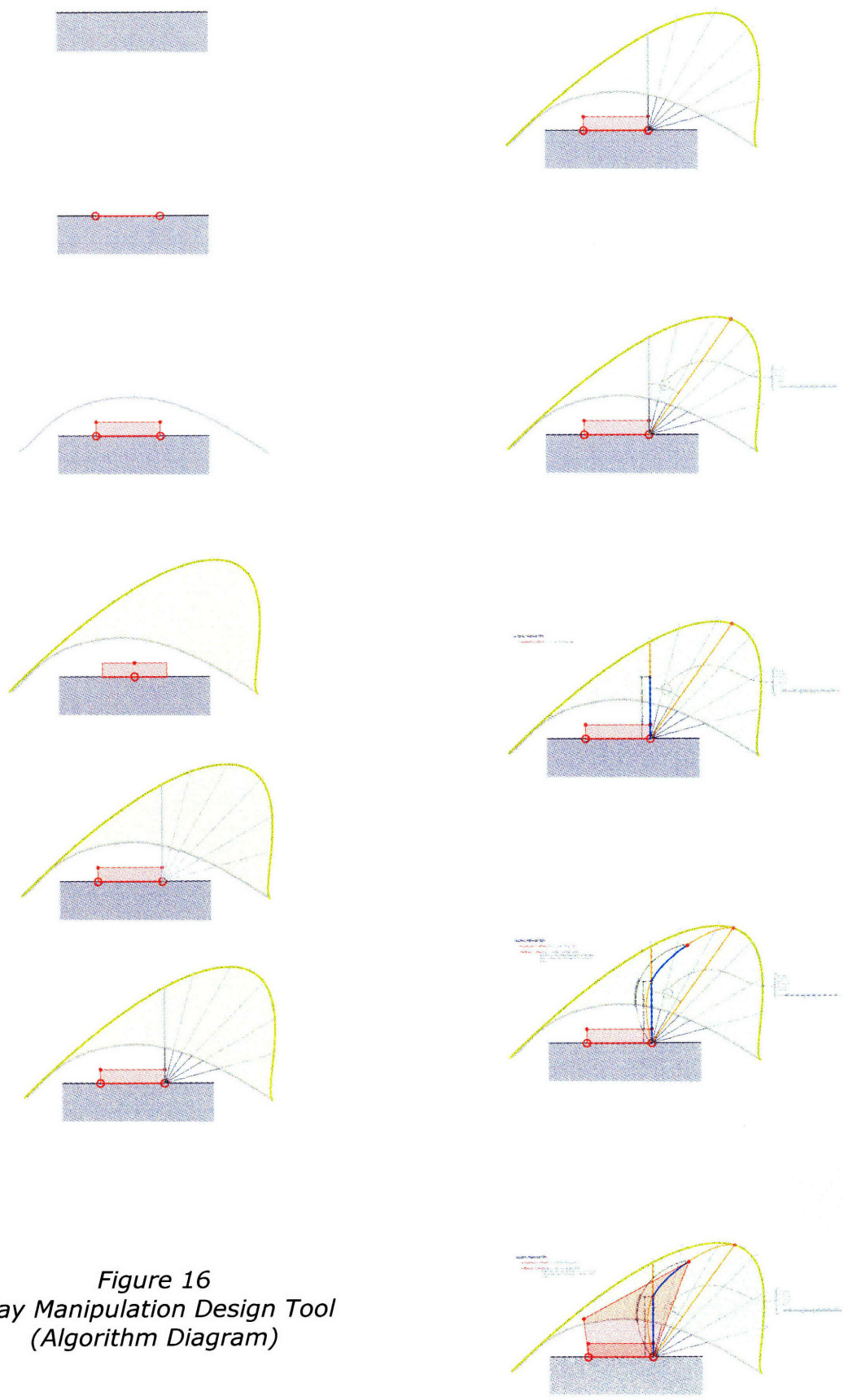


Figure 16  
 Clay Manipulation Design Tool  
 (Algorithm Diagram)

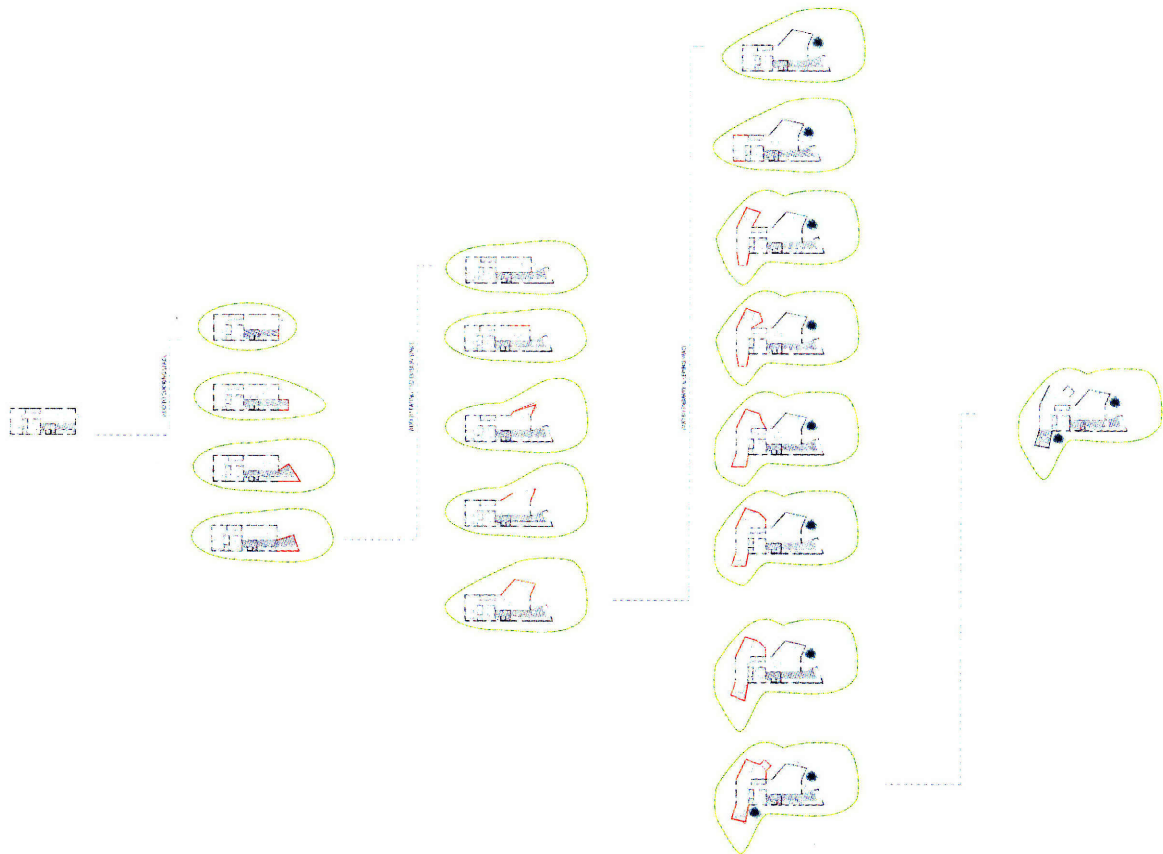


Figure 17 – Clay Manipulation Design Tool (Example Sequence)



## Design Optimization – Inserting Budget into Design

This tool allows for the intelligent automated suggestion for the scaling-back of a homeowner-created design that attempts to maintain the spatial quality of an in-process but over-budget addition design. As computational tools and automated fabrication technologies allow for the precise prediction of the cost of a design, such a tool can bolster the design process by affording the user confidence to design freely but remain within their strict budget. *(Figure 18)*

### Technical Explanation

Computational optimization is not a new concept, however, it's utilization in design applications where non-quantitative, spatial or visual qualities are tantamount has not been explored to a great extent.<sup>124</sup> This is so because mathematical (computational) optimization relies on the ability to provide a value to every cause (or input parameter) and to evaluate the value(s) of its effect (the optimized output parameter(s)). Generally speaking, typical design optimizations dealing with the design of physical artifacts operate in the following manner: A digital model, which may or may not be visualized, is created. Values "defining" this model (dimensions, material properties, etc.) are selected as "input" or "independent" parameters. A second value, the "optimized parameter," is programmed into the optimization algorithm as the result of some form of analysis on the model (e.g. volume, weight, strength, etc.), and a specific "target value," the value that the designer would like the model to yield in this specific analysis, is input into the optimization algorithm. Then, through an iterative process, the computational algorithm alters the values of the input/independent parameters (within pre-defined ranges) then reevaluates the model (repeats the analysis). This process is repeated many times until (1) the analysis yields the desired "target value" within a given tolerance, (2) multiple iterations yield the same value after analysis, meaning that the target value is not able to be achieved by the programmed optimization or with the designed model, or (3) a pre-determined maximum amount of iterations or time for optimization completion is reached, meaning that the problem may be too complex to efficiently optimize

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<sup>124</sup> At the time of this writing and to the knowledge of this author.



(e.g. too many input parameters, conflicting input parameters, obtuse relationship between input parameters and optimized value, etc.). Ideally, an acceptable combination of values for the input set are found to yield a design that conforms to the desired target value under computational analysis.

This process, however, is not immediately applicable to optimizing the homeowner's addition design to fit within their budgetary constraints. While each dimension and every geometrical relationship between all parts of the user's design is known at every given point, and thus the cost of such an addition with these values can be computationally determined (analyzed), the design of a space is not simply the aggregate of each dimension – it is the relationship between these geometric relationships that determines the spatial condition of the design.

Thus, while a typical optimization algorithm will attempt to alter the values of the input parameters (within pre-determined ranges) in such a way as to achieve as quickly as possible the target value for the optimized parameter, a valid optimization of an addition design must attempt to maintain the "spatial relationships" of the optimized model.<sup>125</sup> In this thesis, this was achieved by a sort of rationalized "baby steps" optimization algorithm. Each input value is altered in sequence by a very small amount (or, rather, by a certain percentage within a pre-determined range of total resulting value) with each iteration. Thus, while the sizes of elements in the design are changed in the optimization process, the proportions and, ideally, the spatial relationships designed by the user are maintained. Nonetheless, not every type of parameter ought to be altered by the same percentage, or rate, with each iteration. Thus, values such as ceiling heights are altered in the optimization at a much slower rate than wall lengths, for example, as they have a much more dramatic impact on the spatial condition created by the design. In the end, the homeowner's addition design is not simply shrunk, but altered slightly, to fit within their predetermined budget.

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<sup>125</sup> An attempt was made to utilize the built-in Simulated Annealing optimization algorithm in CATIA v5r16's Engineering Module prior to the design of a specific optimization for this thesis. However, the Simulated Annealing algorithm proved to consistently produce results that differed extensively from the original, pre-optimization design.

Another necessary innovation required in this thesis to optimize the addition design to fit within budget is the allowance for a much more “open” optimization process. Indeed, many constraints and automated processes need to be imposed upon the addition design “behind-the-scenes.” While most of these rules are “obvious” and logic spatial constraints, which most users would not themselves transcend when directly manipulating their design, an automated process altering dimensions in the design may in fact cause the resulting model to break a pre-rationalized rule.

For example, any walls falling below a given length<sup>126</sup> are removed by being “nested” between its two adjacent walls. However, such removal of a wall has a nontrivial effect on the cost of the addition. Therefore, if the removal of such a wall is not taken into account whilst the optimization is in process, but, rather, occurs after the optimization is complete, this result will not be accurate as it will not have taken into account the removal of the wall. Therefore, in order for the optimization to operate accurately, it must “open” itself to other automated processes which would occur if the user were manipulating the design. While it would be extremely inefficient for the optimization algorithm to “pause” for these constraint checks to occur, after the target value of the optimization is reached, the algorithm allows for the other automated processes to occur, and if indeed a change in automated (e.g. a wall is removed), the optimization re-commences by backtracking.

The result is an optimization process that is both non-intrusive, in terms of “softly massaging” the homeowner’s addition design, if necessary, into an similar alternative that falls within their budgetary constraints and itself acts as one part of a larger framework of tools facilitating the design process, rather than a very hierarchical, top-down operation as is typical of optimization processes.

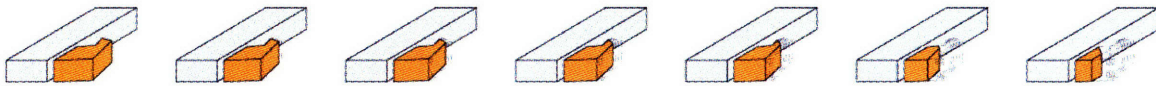
## **Implications**

Flexibility of a design tool can have the reverse effect on a design process if it is not checked by constraints. Indeed, a major present inhibitor to do-it-yourself design-build is uncertainty of cost leading to a fear of “biting off more than one can chew” by beginning

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<sup>126</sup> In the thesis: 1 foot.

a design-build process that will cost more than ones budget allows. When variable labor costs are not a factor, precise and consistent automated fabrication processes affords designers the knowledge of the exact cost of a design<sup>127</sup> based on necessary material amounts and fabrication time;<sup>128</sup> but unless this cost becomes part of the design process the nonprofessional designer may remain in constant inhibiting fear of designing over their budget. A tool such as the one prototyped in this thesis, embedded into the design interface and linked to its processes, which allows the user not only to know the cost of their design but also how they can most easily reduce it if necessary, can remove a significant barrier to homeowner empowerment.<sup>129</sup>



*Figure 18 - Optimization for Budget Explanatory Diagram*

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<sup>127</sup> Harfmann ("Implementation of Component Based Design") describes the cost-prediction benefits derived from much less sophisticated digital organization systems for single-family residential construction. (Harfmann, p. 227)

<sup>128</sup> "Indeed the very purpose of digital tools and technologies is to eradicate unpredictability and anomaly[...], both in the process and the product toward an enterprise of utter predictability." (Harrop, p. 71)

<sup>129</sup> Kilian, in "Linking Digital Hanging Chain Models to Fabrication," warns, however, that optimization must be considered in terms of "opening up potential design paths to the designer in light of environmental influences," and not as "the sole driver in the design." (Kilian, p. 122)

## MATERIAL SELECTION: STRUCTURAL INSULATED PANELS

Automated fabrication technologies have virtually no limitations with regard to materials.<sup>130</sup> However, in the interest of efficiency, it is best to reduce the amount of different materials, as each may require its own mechanism in the factory for securing it as it is being processed (cut, drilled, etc.) or, at least, its own tool attachment for the automated fabrication machine. In an ideal automated fabrication schematic, one single material would be used in the assembly of the desired product.

A house assembly, however, requires a great multiplicity of material properties to achieve functionality. Even discounting exterior cladding and interior finishes (which will not be an included feature of the components fabricated and shipped to the homeowners for their additions<sup>131</sup>), a simple wall must perform two mutually exclusive functions: provide structural stability and insulate the home from energy transfer.

Another option does exist: composite materials. Composite materials are essentially single pieces of “material” composed of multiple raw materials. When used in the creation of single-family residences, these composites are often called “panels.”

Panelized systems for single-family housing have existing as early as the 1830’s with the “Manning Personal Cottages” used by British colonists.<sup>132</sup> The Lustron houses were panelized, as were the Packaged Houses.<sup>133</sup> In the case of the latter, Konrad Wachsmann utilized a prefabricated, factory-cut to size wall panel composed of a rigid insulating material sandwiched between two layers of wood<sup>134</sup> – a precursor to one of the most interesting building systems that is presently gaining salience in American residential construction: the Structural Insulated Panel (SIP). (*Figure 19*)

SIPs were invented as early as the 1950s.<sup>135</sup> While able to be composed of many different combinations of materials with slightly differing properties, the most common SIP is comprised of a interior layer of Extruded Polystyrene (EPS) for insulation between two layers of Oriented Strand Board (OSB) for structural strength (and as a nailing-board for the application of cladding materials onto each

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<sup>130</sup> Thompson, p. 182

<sup>131</sup> Discussed below.

<sup>132</sup> Davies, p. 47

<sup>133</sup> See Knerr, *Suburban Steel*, for details on the Lustron House panelized system and Herbert, *The Dream of the Factory-Made House*, for details on the Packaged House panelized system.

<sup>134</sup> See Herbert, *The Dream of the Factory-Made House*, for details on the Packaged House panelized system.

<sup>135</sup> Student of Frank Lloyd Wright and founder of the Dow Chemical Company, Alden B. Dow, is credited for the creation of the first SIP in 1950. He built some of the first SIP-built houses in Midland, Michigan, some of which are still occupied. (Morley, p. 8)

side).<sup>136</sup> These layers are secured together by means of a very strong epoxy.<sup>137</sup> In a single sheet material, SIPs typically perform both structurally and as insulation in a manner superior to the stud-insulation-sheathing assembly typically employed in stick-built single-family housing in the United States.<sup>138</sup> (Figure 20)

Beyond performance, SIPs exhibit many advantages over traditional “platform” (stud wall) framing systems. A SIP wall of the same size (and performance) is lighter than a stud wall by virtue of its being comprised of a lesser percentage of high-density material (wood). SIP systems are typically easier and faster to assemble into homes, as a good part<sup>139</sup> of the system is remanufactured *into* the panel. And, perhaps most importantly, almost all processing (cutting, drilling, etc.) of a SIP wall, roof, etc. can be completed by a single automatic fabrication machine.

The Structural Insulated Panels designed for this thesis have two main modifications to the typical, commercially available SIPs: (1) the interior sheet of sheathing is 1/4in thick and is finish-grade MDF<sup>140</sup>, rather than the typical 1/2in OSB utilized in standard SIPs,<sup>141</sup> and (2) the EPS insulation used will be of an insulation value (r-value) superior to typical, commercially available SIPs,<sup>142</sup> but will be only 3.5in thick for regular walls and 5.5in thick for walls containing plumbing conduits.

The reasons for the modifications are as follows: Without the need to add an additional step to the fabrication process of the panelized addition components, the use of a finish-grade material on the interior side of the panel can replace the expensive “finishing” of the interior with gypsum wall-board.<sup>143</sup> As MDF is extremely strong, its thickness can be reduced to maintain equal weight as well as strength. Secondly, reducing the thickness of the EPS insulation between the two layers of sheathing by means of a higher quality material grade is done for the purpose of facilitating assembly and reducing waste in the production lifecycle of the addition components. Not only are thinner panels easier to maneuver during the do-it-yourself addition assembly process, their reduction of thickness will require less volume of space in the factory and, perhaps most crucially, during transportation to the site.

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<sup>136</sup> See Morley, *Structural Insulated Panels*, pp. 20-29 for a detailed description of SIP material compositions and manufacturing processes.

<sup>137</sup> See Morley, *Structural Insulated Panels*, pp. 26-27 for a detailed discussion of SIP adhesive technology.

<sup>138</sup> See Morley, *Structural Insulated Panels*, pp. 29-37 for a detailed discussion of SIP performance features and comparisons to typical, stick-built construction.

<sup>139</sup> e.g. structure, sheathing, insulation, plumbing conduits, and electrical conduits

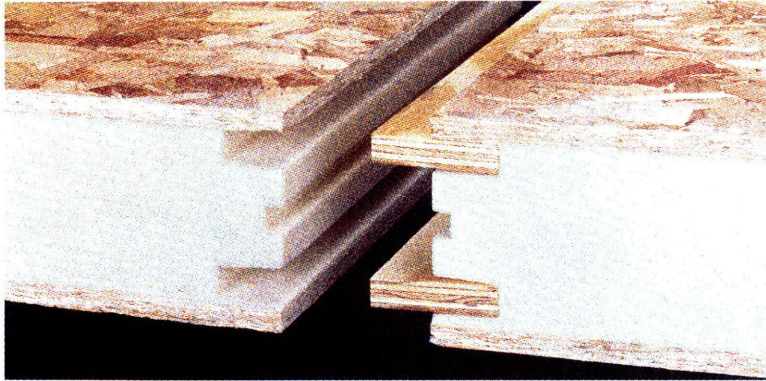
<sup>140</sup> “Medium Density Fiberboard”

<sup>141</sup> Morley, pp. 21-22

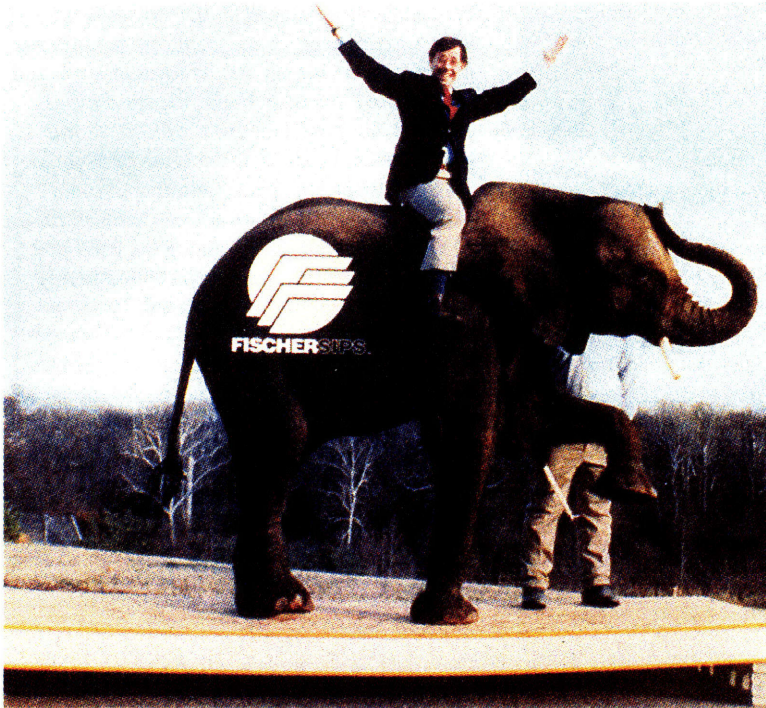
<sup>142</sup> Morley, pp. 23-25

<sup>143</sup> Morley, p. 23





*Figure 19 - SIP Panels  
(Image: Morley, p. 21)*



*Figure 20 - Fisher SIPS Advertisement Demonstrating SIP Strength  
(Image: Morley, p. 30)*



## FABRICATION SCHEMATIC

### Background

#### Mass Production

Industrialization did not develop in the United States until the second half of the 19<sup>th</sup> century.<sup>144</sup> Essentially, to industrialize a production process is to order and coordinate the process such that it produces the desired artifact in a predictable and efficient manner by making the best use of human and machine labor.<sup>145</sup> And, the early 20<sup>th</sup> century, Henry Ford's famous production system, assembly-line mass production – or *fordism* – had followed a much more narrow tack. Assembly-line and mass-production focused primarily on lowering costs.<sup>146</sup> Mass-production benefits from the principal of "economies of scale" and standardization; a process can become extremely efficient if it can make one artifact many times as quickly as possible because all machinery and labor is "optimized" for the production of this product.<sup>147</sup> Thus, as long as a large percentage of the products are purchased, profit increases with volume.<sup>148</sup> Assembly-line production repeats mass-production at the scale of the individual production process. In a fractal-like manner, each operation done to a product in an assembly line is, itself, "mass produced," meaning that the labor and/or machinery and space utilized to do this particular operation (e.g. paint, bolt, test, etc.) is dedicated uniquely to that operation.<sup>149</sup> Thus, the labor/machinery/space can be optimized to do every operation that occurs in the process of mass producing a product.

In the homebuilding industry, mass-production has been utilized extensively in the building of large, speculative suburban developments, the most famous of which, perhaps, being

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<sup>144</sup> Pine, p. 9

<sup>145</sup> Pine, pp. 10-14

<sup>146</sup> Prior to *Fordism*, American industrialized production was hailed as a harmonious hybrid of machine efficiency and craftsperson innovation and quality. (Pine, p. 16)

<sup>147</sup> Pine, pp. 16-17

<sup>148</sup> "Since lowering costs meant prices could also be lowered, an internal logic came into play in the development of Mass Productions. As prices were lowered, more people could afford to buy the products, resulting in greater sales and therefore greater production, and even lower costs, and so on." (Pine, p. 16)

<sup>149</sup> This system of "division of labor" was part of the "American System," (prior to Mass-Production) as reported by the 1854 British report: *The American System of Manufactures*. (Pine, p. 301 (end notes)), however, Pine explains how this was implemented to the extreme in *Fordist* production: "[...]workers [became] so specialized that[...] they performed the smallest of functions, over and over, in the assembly-line production of a single part." (Pine, p. 19)

Levittown. By producing only two different house designs in the creation of a 17,500 home development,<sup>150</sup> Levit and Sons did indeed treat the flat land on which he built as a large factory, with workers moving from station to station (house to house) performing a single construction operation in sequence until the development was completed.<sup>151</sup> This process of purchasing large tracts of land to be subdivided into plots for the production of a very few number of designs for hundreds or thousands of houses prior to their commission or sale is very common throughout the United States.

Mass-production, however, has severe faults, particularly in the contemporary economic landscape. Inherent in all production processes is error, but mass production is particularly ill-equipped for efficient quality control (error handling). The fractal, assembly-line nature of traditional mass-production processes typically yields internal inventories of parts awaiting assembly into the final product,<sup>152</sup> and each of these parts are themselves produced by a series of mass-produced processes independent from each other and only linked by sequence.<sup>153</sup> Thus, if one operation in this large matrix of mass-produced operations develops an error, this error will not be found until quality-control testing at when the product is assembled.<sup>154</sup> By this point, many, many parts, sub-assemblies, and assemblies have been produced containing that same error<sup>155</sup>.

This same mass-produced error phenomenon can also occur, again in a fractal manner, in the next scale up: the product inventory. Mass-production operates on the principal that a constant demand for the product being mass-produced exists, and thus it is statistically and economically valid to produce many of these products on the speculation that most will be met with demand once produced. However, if a change in tastes, demands, needs, or economic condition occurs, again the process is left with many products into which it has poured invested capital but cannot sell. This problem is particularly relevant in the present economic landscape as tastes, demands,

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<sup>150</sup> Kelly(2), p. 27

<sup>151</sup> Kelly(1), p. 26

<sup>152</sup> This process creating in-process inventory is called "batch and queue." (Liker, p. 88)

<sup>153</sup> Pine, p. 19

<sup>154</sup> Liker, p. 29

<sup>155</sup> "Because by the time a defective piece works its way to the later operation where an operator tires to assembly that price, there may be weeks of bad parts in process and sitting in buffers." (Liker, p. 29)

and even economic conditions<sup>156</sup> can change rapidly and without prediction.<sup>157</sup>

## Lean Manufacturing

Such issues of waste in mass-production were the impetus for the development of Lean Manufacturing.<sup>158</sup> Lean Manufacturing<sup>159</sup> is essentially a restructuring of the way producers look at the mass-production process with a constant goal of reducing *muda*, or waste, by eliminating, among other causes of *muda*, the maintenance of inventories.<sup>160</sup> The elimination of inventory is the first and most concrete step in the combat of the above stated problems in mass-production: never should physical capital (materials, parts, sub-assemblies, assemblies, finished products, etc.) be held static during the production process.<sup>161</sup> This serves to disrupt the above described fractal nature of earlier attempts to increase efficiency in mass-production by creating mini-production systems for each operation in the production of a finished product and assembling these components downstream in the process. This mantra, spanning the entire lifecycle of the product from the acquisition of raw materials to the end-user sale of the finished product,<sup>162</sup> can be said to lead into concept of mass-customization.

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<sup>156</sup> See Pine, p. 31, for an explanation to why the US economy is far less stable in terms of demand than when Mass Production began.

<sup>157</sup> In early 20<sup>th</sup> century America, the desire for product variation was slow to develop relative to Europe due to the much less economic differentiation of social classes and the relatively new availability of inexpensive industrialized products. This, coupled with an acute seller's market, had made possible the imposition of standardized products onto American consumers. (Pine, pp. 17-18) However, Pine (p. 30) postulates three causes to why homogenous, standardized production (and therefore products) is no longer viable:

1. The growing diversity in the United States with regard to "class, race, gender, lifestyles, and national origin."
2. Increasing income disparities create demands for different products.
3. The American markets is growing far more slowly, requiring new products to serve old demands as the availability of unfulfilled demands diminishes.

<sup>158</sup> The quintessential innovator of Lean Production, "Toyota saw [waste] as an inherent flaw in Ford's production system." (Liker, p. 22)

<sup>159</sup> For an excellent introduction to Lean Manufacturing, see Liker, *The Toyota Way*

<sup>160</sup> "Ohno [Toyota's lead engineer] considered the fundamental waste to be overproduction, since its causes most of the other wastes. Producing more than the customer wants by any operation in the manufacturing process necessarily leads to a build-up of inventory somewhere downstream: the material is just sitting around waiting to be processed in the next operation." (Liker, 29)

<sup>161</sup> Inventories of in-process parts in Mass Production are called "buffers" and are considered waste in Lean Production. (Liker, p. 29)

<sup>162</sup> See Liker, *The Toyota Way* for an in-depth explanation of Lean Manufacturing.

## Mass-Customization

Put simply, mass-customization is an economic concept<sup>163</sup> stating that flexible production methods affording to the efficient production of variation throughout the entire lifecycle of a product<sup>164</sup> actually leads to profit margins equal or greater than the ultra-efficient mass-production of a single, immutable product.<sup>165</sup> While, in architecture, mass-customization is often misconstrued into the overly limited definition of the provision of customized products to individual customers,<sup>166</sup> this end-user marketing strategy<sup>167</sup> is but one side-effect of mass-customization principals, which begin at the highest levels of corporate management down to the smallest details of production.<sup>168</sup> In the construction industry, an example of mass-customization could be the system of “interchangeable” subcontractors from which the general contractor can select on a project-by-project basis, or the use of standard 2x4 stud framing at 16in OC intervals allowing for the rationalized and efficient (relative to previous systems) erection of a large variety of architectural forms for different markets, sites, customers, etc, even if this variation occurs prior to customer demand. And, while visionaries such as Albert Bemis developed sophisticated schemes as early as the 1930’s for the production of actual demand-driven mass-customized homes, they were never implemented at any relevant scale.<sup>169</sup>

### “Pull” Theory and Mass-Customization

While mass-customization itself is not strictly an end-user focused concept, lean manufacturing would indeed tend to move towards frontloading the production system in this way due to a

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<sup>163</sup> As described by Stan Davis and B. Joseph Pine II in the latter’s *Mass Customization: A New Frontier in Business Competition*.

<sup>164</sup> For a general case study introduction to this shift in the automobile industry, see Pine, p. 35.

<sup>165</sup> For an introduction to Mass Customization within an architectural setting, see Kolarevic, p. 52.

<sup>166</sup> As exemplified in Hanna, p. 79.

<sup>167</sup> Surjan, p. 139

<sup>168</sup> See Pine, *Mass Customization*, for a detailed discussion of the necessary structural changes in a corporation dedicated to Mass Customization.

<sup>169</sup> Alfred Bemis developed an intricate system he entitled “modular coordination.” While the system was highly well developed as part of his three volume tome *The Evolving House*, it was never seriously implemented. (Bemis, *The Evolving House*, Knerr, pp. 35-6, and Davies, p. 134)

higher-level concept of Lean Manufacturing: "pull".<sup>170</sup> In the attempt to remove waste and inventory, the concept of "pull" demands that all production processes must follow from direct demand<sup>171</sup> – in other words, the mass-production hierarchy is thus reversed as *downstream* processes drive the process.<sup>172</sup> While, at the level of the finished production, this may seem to be the *status quo* of standard free-market economics: market demand drives the product of goods to fill this demand. However, efficiencies afforded by mass-production led to an economy of very large production firms producing at will and, in fact, "pushing" demand on the market.<sup>173</sup> Like mass-production itself, this works very well when the economic landscape is a "seller's market," so to speak.<sup>174</sup>

In a "pull" production system, the entire process, at least conceptually, begins with the end-user demand for a specific production, which, once in the production system, leads to the demand for the necessary assemblies to create the product;<sup>175</sup> leading to the necessary parts for these assemblies; to the necessary production operations for the parts; and the desired raw materials for these operations.<sup>176</sup> A production system equipped for mass-customization will be capable of meeting this demand else a new one must be created.

Thus, it is indeed conceptually possible to provide demand-driven variation ("customization") at the level of the end-user product if the entire production system is able to handle a high level of variation.<sup>177</sup> This variation must begin at the design phase (as discussed in an earlier chapter) and, ideally, carry through to the level of corporate structure.

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<sup>170</sup> Also referred to as "Just-in-Time" (JIT) manufacturing. (Liker, p. 23) While both *Fordist* mass-production and Lean Manufacturing speak of production "flow", (Pine, p. 15 and Liker, pp. 87-103) the term "pull" aids to differentiate Lean Manufacturing from *fordist* mass-production, which can be qualified as "push." (Liker, p. 104)

<sup>171</sup> Liker, pp. 106-108

<sup>172</sup> According to Knerr, p. 15, the Lustron Corporation (see above) had employed "pull" or "just-in-time" manufacturing.

<sup>173</sup> Pine, p. 18 and "production driven market?"

<sup>174</sup> Pine, p. 18

<sup>175</sup> Hanna and Mahdavi ("Modularity and Flexibility at the Small Scale") presents the example of Levi apparel company's "Personal Pair" program "that provided custom fitted jeans based on measurements taken at selected shops." (Hanna, p. 79)

<sup>176</sup> This description is a simplification of the actual process, which requires many more interstitial processes and intricacies. It is interesting to note, however, the extreme reversal this implies relative to the highly hierarchical, *Taylorist* and "vertically integrated" corporate structure exhibited in Mass Production. (Pine, p. 20)

<sup>177</sup> According to Patrick Harrop ("Agents of Risk: Embedding Resistance in Architectural Production"), for example, that mass-customization tools (e.g. CNC tools) have "allowed the individual designer to manufacture unique 'one-offs' without debilitating overhead posed by the expensive retooling of machinery, molds, and dyes." (Harrop, p. 67)

## **Fabrication Methodologies**

### **Pre-Industrialized Fabrication Methodologies**

“Artisanal” is often the term given to pre-industrialized/rationalized fabrication methods.<sup>178</sup> Typically, these fabrication methodologies required a highly skilled craftsperson able to perform all of the operations required to fabricate the parts or products in question, often moving from raw material to final assembly.<sup>179</sup> The tools of this production system were inseparable from the labor (in this case, the artisan) in that the tools served only as an interchangeable part of the artisan’s hand.<sup>180</sup>

### **Mass-Production Fabrication Methodologies**

Mass-production fabrication found efficiencies in separating out each operation in the fabrication process into separate sub-processes, each with its own tools and labor force.<sup>181</sup> Mechanized tools are here used to reduce the necessary skill possessed by the human labor<sup>182</sup> as the need for multifariousness is supplanted by assembly-line sequencing described above. Therefore, the tools of this system were typically rather simple in operation,<sup>183</sup> but were able to handle very large volumes to “push” the “products” of their processes down to the next process.

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<sup>178</sup> Pine, p. 9

<sup>179</sup> Pine, pp. 9, 13, and 19

<sup>180</sup> Pine, p. 19

<sup>181</sup> “The path to Mass Production led from artisans responsible for producing an entire product by their own means and at their own pace in Craft Production, to groups of (still) craftsmen working together on a defined product or at least a significant component of one in the American System, and finally to workers becoming so specialized that, under the close direction of a supervisor, they performed the smallest of functions, over and over, in the assembly-line production of a single part.” (Pine, p. 19)

<sup>182</sup> Pine, p. 10

<sup>183</sup> “The degree of specialization [in Mass-Production] applied to machinery was very similar. In Craft Production, craftsman used a relatively small set of general purpose tools to perform all of their operations. In the American System, once general-purpose machines adapted to specialized functions provided the means of producing greater numbers of more sophisticated products. But in Mass Production, the entire production process became critically dependent on specialized machines that performed one, and only one, function[... and] as workers perform[ed] smaller and smaller tasks, these tasks became easier to automate.”(Pine, p. 19)



## Automated Mass-Customized Fabrication Methodologies

Ironically, pre-industrial, “artisanal” fabrication methodologies were often in fact exemplary of mass-customization theory.<sup>184</sup> Contemporary advances in automated mass-customized fabrication methodologies returns to the use of multifarious production processes<sup>185</sup> but continues the trend of reducing the role of human labor in the fabrication process.<sup>186</sup> Here, highly dexterous tools,<sup>187</sup> now generally labeled CNC (Computer Numerically Controlled), are able to accept a set of “instructions,”<sup>188</sup> in the form of computer code, that “pull” from the tool a large variety of artifacts.<sup>189</sup> CNC tools range from being limited to one simple operation (similar to the tools of mass-production) to “robots” able to perform a large variety of operations.<sup>190</sup>

### Automated Fabrication: CNC Technology

Computer Numerically Controlled fabrication<sup>191</sup> tools have their origins in the Numerically Controlled (NC) machines developed at MIT in the 1950’s.<sup>192</sup> A kind of robot, CNC machines are receive instructions (“gcode”)<sup>193</sup> dictating the a certain series of movements that it must perform while milling, grinding, sawing, or otherwise removing material to fabricate an artifact from a piece of raw material.<sup>194</sup> CNC machines can be categorized into two types of movement types: lathes (for creating artifacts with, typically, curvilinear sections through spinning) and axial machines.<sup>195</sup> (*Figure 21*) Unlike lathes, axial

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<sup>184</sup> Pine, p. 48, explains that only the need to drastically reduce costs differentiates Mass Customization thinking from Craft Production. Further, Harrop contends that automated fabrication processes, combined with digital modeling techniques, continues and goes beyond the tradition craft. (Harrop, p. 67)

<sup>185</sup> Schodek, p. 16 and Pine, p. 19

<sup>186</sup> Harrop, p. 67

<sup>187</sup> “CNC machining is versatile and widely used, competing with many other processes.” (Thompson, p. 184)

<sup>188</sup> Schodek, p. 13

<sup>189</sup> “Almost every factory is now equipped with some form of CNC machinery. Therefore, applications are diverse and widespread across the manufacturing industry.” (Thompson, p. 183)

<sup>190</sup> Harrop, p. 67.

<sup>191</sup> For a detailed introduction to CNC fabrication within an architectural context, see Kolarevic, pp. 34-36. For an introduction to CNC fabrication in general, see Thompson, p. 183 (sidebar).

<sup>192</sup> Schodek, p. 24

<sup>193</sup> For an introduction to the principals of *gcode*, see Kolarevic, pp. 34-35.

<sup>194</sup> Schodek, p. 4 (Note that CNC machinery performing other tasks, such as welding, also exists.)

<sup>195</sup> Thompson, p. 183

CNC machines do not spin the raw material but rather move it or the cutting tool in a series of straight, axial movements,<sup>196</sup> but can also, through a rapid series of straight movements, interpolate curved movements. Further, some axial CNC machines, often called 5-axis, tilt either the tool arm or material to allow for all-round removal of material in the creation of a three-dimensional object.<sup>197</sup> (Figure 22 & 23) Finally, when combined with robotic machines for assembly and the movement of materials and parts, a CNC-enabled factory can produce an entire product without human labor.<sup>198</sup>

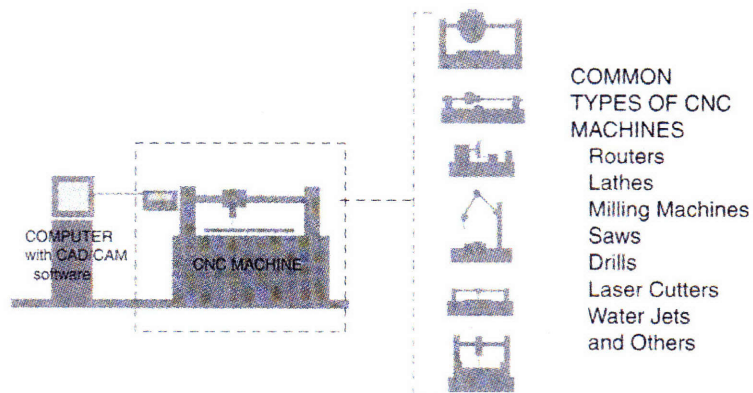


Figure 21 - CNC Explanatory Diagram  
(Image: Schodek, p. 13)

<sup>196</sup> Kolarevic, p. 34

<sup>197</sup> Kolarevic, p. 34

<sup>198</sup> "In addition to [CNC fabrication], a fully automated design and production environment might also include material handling systems, robots for assembling parts, machine vision systems, process management and control systems, material resource planning systems, quality assurance systems, and a whole host of other possible systems and technologies." (Schodek, p. 4 )

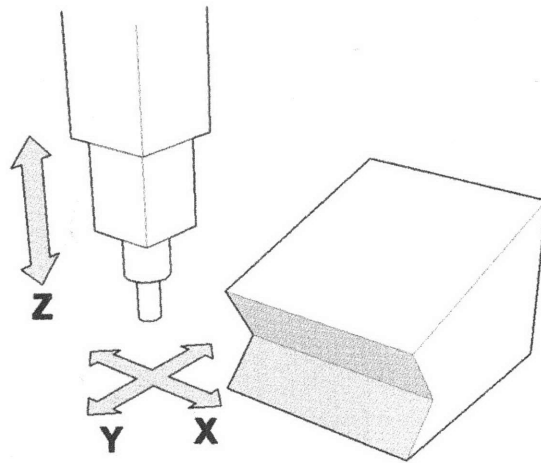


Figure 22 - Three-Axis CNC Explanatory Diagram  
(Image: Kolarevic, p. 35)

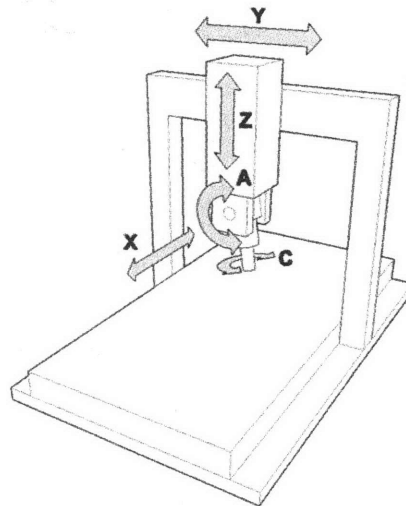
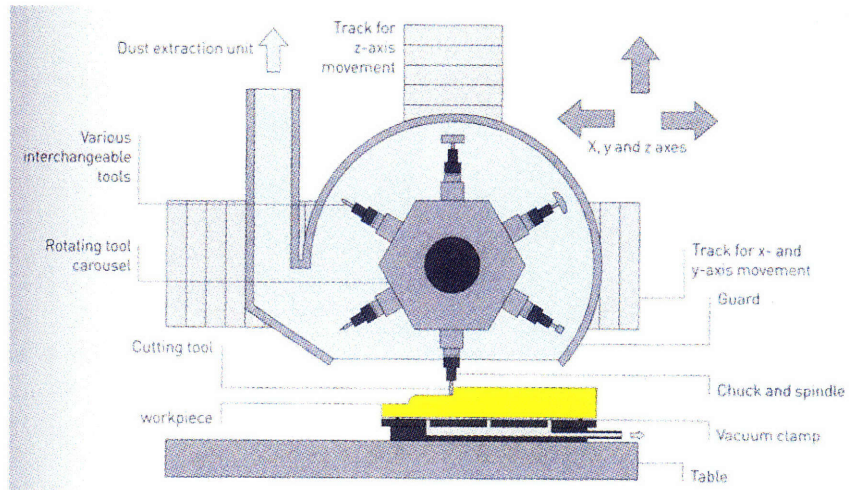


Figure 23 - Five-Axis CNC Explanatory Diagram  
(Image: Kolarevic, p. 35)



**Figure 24 - Multi-Tool CNC Explanatory Diagram**  
*(Image: Thompson, p. 183)*



## Proposed Production System

For this thesis, the proposed production system is a fully automated “pull” manufacturing facility for the mass-customized production of flat components for delivery to site and do-it-yourself assembly by the homeowner. By virtue of its being created within a parametric framework, the digital model designed by the homeowner can be automatically translated into CNC language (“gcode”),<sup>199</sup> which can be electronically sent<sup>200</sup> to the automated factory<sup>201</sup> and trigger a truly “pull” production system.<sup>202</sup>

### The Factory

For the purpose of illustration, a schematic design for such a “pull” production system factory was proposed. The factory, rather than a large warehouse where large inventories of standard parts are stored for future assembly into products, can be seen as one large, automated CNC machine<sup>203</sup> where both tools and materials move towards the efficient creation of parts for a single addition order that are shipped to the site for immediate homeowner assembly.<sup>204</sup> For purposes of description, the production machine can be subdivided into eight positions, or “cells”,<sup>205</sup> which are spatially divided to allow for the non-intersection passage of automated tools along gantries. *(Figure 25)*

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<sup>199</sup> An example of this process can be found in Anzalone, p. 153.

<sup>200</sup> Branko Kolarevic, *Architecture in the Digital Age*, calls this “file-to-factory.” (Kolarevic, p. 31)

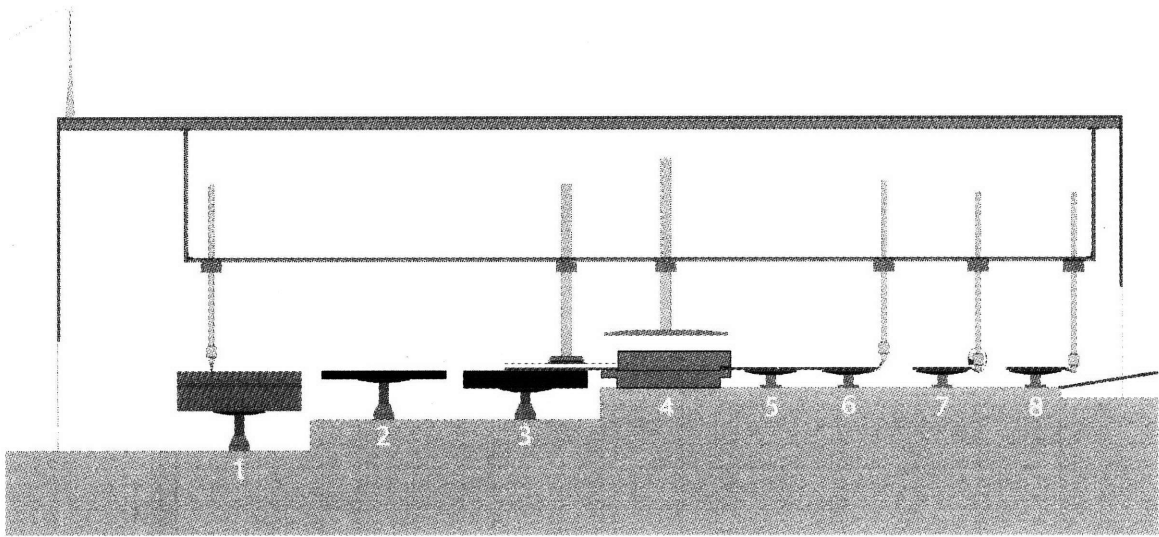
<sup>201</sup> “Most CNC machining is almost completely automated, with very little operator interference. This means that the process can run indefinitely once started, especially if the CNC machine is capable of changing tools itself.” (Thompson, p. 185)

<sup>202</sup> “The great power of CAD/CAM technologies comes into play when the core systems are embedded in a larger networked information system that brings into play the full spectrum of participants[...].” (Schodek, pp 4-5. Also see Kelmans, p. 37.

<sup>203</sup> Also called a “machining center,” Schodek, p. 13. (Also see Schodek, p. 4, for a technical introduction to versatile automate fabrication.) The systems goal here is to reduce, as much as possible, the production lifecycle of the home, and central tenet to Mass Production, as described in Pine, p, 46, that allows for rapid response of consumer demand.

<sup>204</sup> Unlike Mass Production structures, which attempt to lengthen the production lifecycle as long as possible to increase specialization, (Pine, p. 26) the goal here is to minimize the lifecycle as much as possible to reduce waste.

<sup>205</sup> Schodek, p. 13



*Image 25 - Proposed Factory Schematic*

### **Positions 1 to 3:**

Here the exact number of required raw material sheets – EPS foam, interior sheathing, and exterior sheathing, respectively – are positioned to be “pulled” towards the creation of the required mass-customized Structurally Insulated Panels (SIPs). Also at Position 1 is where conduits are milled out of the EPS foam for electrical and plumbing. *(Figure 26)*

### **Position 4:**

At Position 4 is where a single SIP is applied with epoxy, pressed, and cured on its way to being customized into the precise shape and joint system prescribed by the parametric model of the homeowner’s addition design. *(Figure 27)*

### **Positions 5 to 6:**

At this point, the newly pressed SIP is pulled towards a robotic CNC saw that cuts the panel into the length and at the joint angle as proscribed by the parametric model.<sup>206</sup> This same five-axis tool drills the necessary pockets into the foam edge of each panel for the required drilling block and pre-drills aligning holes into the SIP for assembly facilitation. *(Figure 28)*

### **Position 7 to 8:**

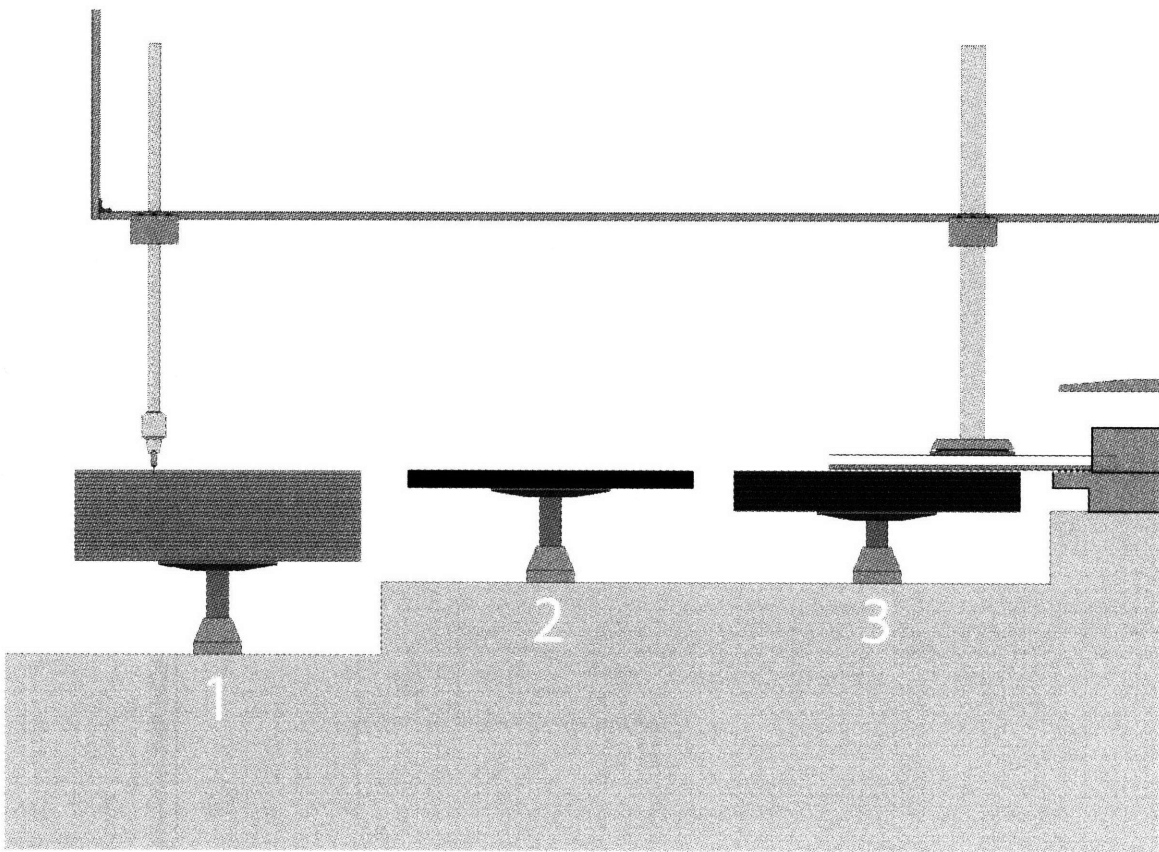
Final processing of the component occurs at these stations, which inject high-strength epoxy into the bolting block pocket and place the block respectively. These stations highlight the dexterity of automated fabrication techniques, where virtually the same tool rigging and system can accommodate a host completely unique tool types. From here the panels are “pulled” by the transportation vehicle and, by virtue of their having been directed by a parametric model capable of assembly sequence simulation to be fabricated in reverse chronological order,<sup>207</sup> can arrive on the site ordered for one-at-a-time assembly by the homeowner. *(Figure 29)*

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<sup>206</sup> See Bechtold, p. 93 for an case study example of a similar CNC fabrication process using SIP-like panels.

<sup>207</sup> Tools such as “4D CAD,” developed at Stanford University by the Center for Integrated Facility Engineering (CIFE), can be integrated within parametric software platforms (e.g. CATIA) for the rationalization of assembly sequences. An early

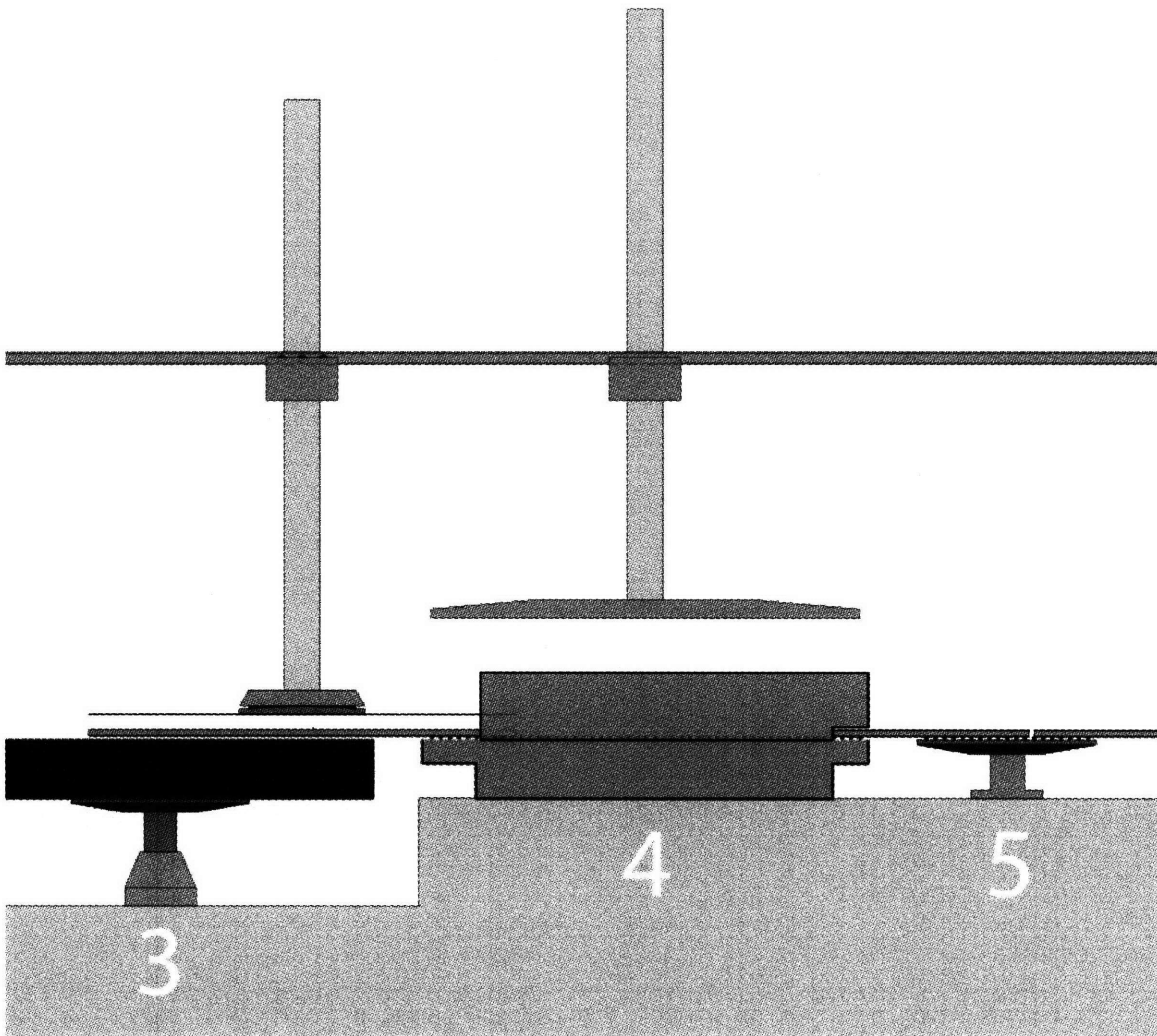




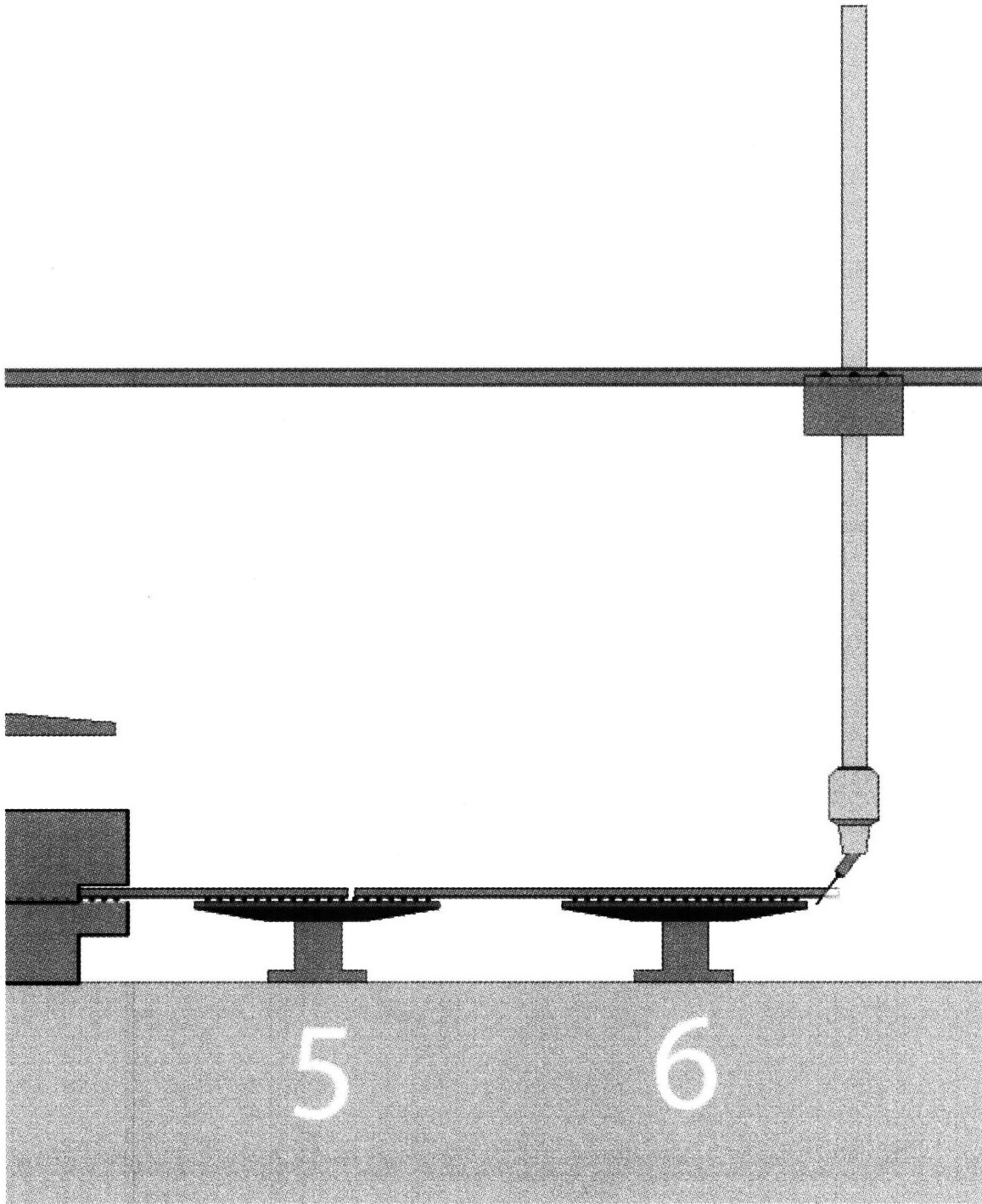
*Figure 26 - Factory Schematic - Positions 1 to 3*

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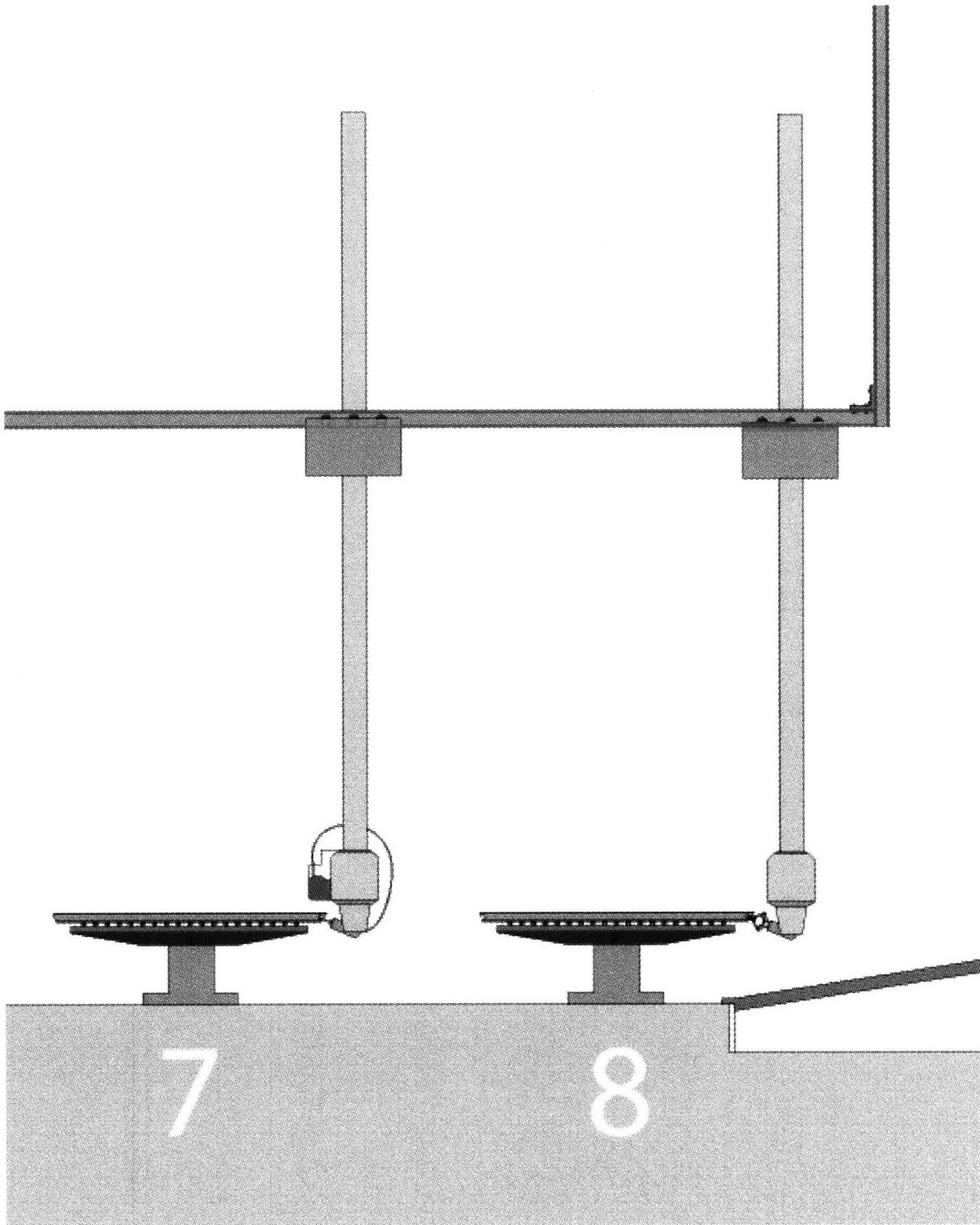
example of this burgeoning technology was used at the Disney Concert Hall in Los Angeles, CA by Gehry Partners. (Matsushima, p. 213)



*Figure 27 - Factory Schematic – Position 4*



*Figure 28 - Factory Schematic - Positions 5 to 6*



*Figure 29 - Factory Schematic – Positions 7 to 8*

## **ASSEMBLY SYSTEM**

### **General System**

The proposed assembly system is modeled after the extant, efficient assembly mechanism used in typical SIP construction. Rather than re-invent a new system, the goal was to adapt the existing details for the demands of CNC fabrication and self-assembly. Most important to the ability to self assemble the additions is the precise, factory-fabrication of each panel and its tagging with information helping the do-it-yourself assembler to locate it within the assembly. Precisely fitting components not only prevents the need to post-process on-site, but also aids in the assembly like the joinery of a jigsaw puzzle – if it fits, it’s right. Further, all panels must be pre-drilled to prevent mistakes in securing the panels.

### **Connection to Site**

As discussed earlier, a do-it-yourself system for addition assembly must not necessitate the use of a traditional, excavated foundation. It is proposed in this thesis that the Starter Home and subsequent additions’ connection to the site is achieved through raised pylons above self-digging footings. After the position of each footing on the site is determined<sup>208</sup>, a small shaft for the footing is dug into the topography, and the footing is inserted into the dug shaft. At this point, the self-digging mechanism of the pylon footing is deployed, creating a larger pocket into the earth for the facile pouring of residential-grade concrete – securing the pylon. Once secure, the footing also utilizes a slip-joint, making possible slight modifications in its height for leveling the addition.

### **Footprint Layout**

Once all of the pylons are secured into the site, a customized steel girder is secured on top of the footings, connecting them and forming the footprint of the addition. While providing added rigidity to the raised “foundation” assembly, this girder also acts to create a “self-guided” assembly of the floor and wall panels, creating a cradle into which they are precisely positioned. Further, the girder creates a drip-edge where the superstructure of the addition connects to the

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<sup>208</sup> This could be aided by near-future innovations in GPS measuring devices, for example.

pylons, preventing water from seeping into the substructure and eroding the footings over time.

### **Floor Panel Layout and Wall Erection**

The size of the floor and wall panels are limited in width to three feet, enabling their easy manipulation on-site by non-professionals. The floor panels are inlaid into the girder in a manner similar to interlocking floorboards. Each is inserted into the other (*Figure 30*) and bolts are drilled into the pre-drilled holes. The wall panels are erected in the same manner. All window and door jambs are pre-manufactured into the respective wall panels, as well as the plumbing and electrical systems.

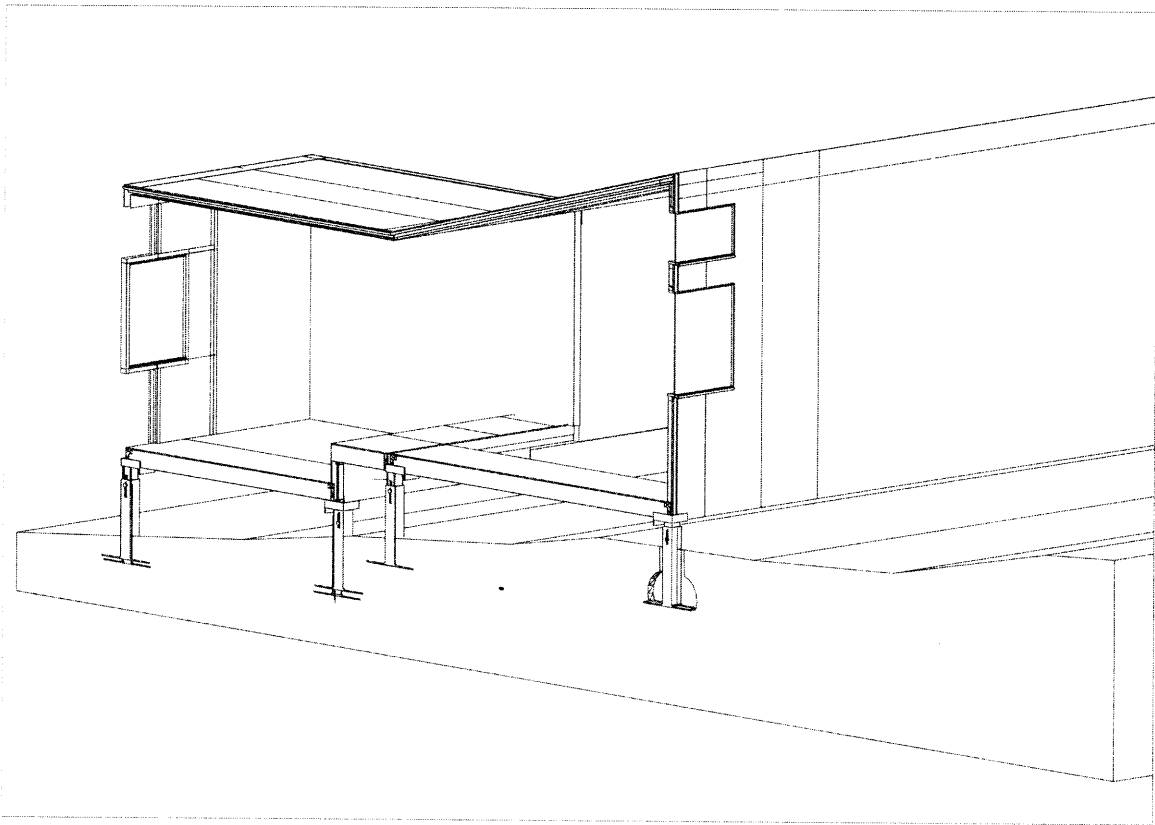
### **Roof Assembly**

Capping the interconnected wall panels is a V-shaped steel section that aides to secure them laterally, particularly important because of the multitude of joints between panels due to the limitation of the panel size for easy on-site manipulation. The other segment of the V-section receives the roof panels, which are installed in a manner similar to the floor panels. The V-shaped steel section not only aids in securing the wall and roof panels against lateral loads, but like the steel girder securing the floor panels, it also aids in directing the assembly. Again like the steel girder, it is custom formed for the homeowner's addition design such that it ensures that the correct amount and placement of wall and roof panels is achieved, as well as establishing that they remain level.

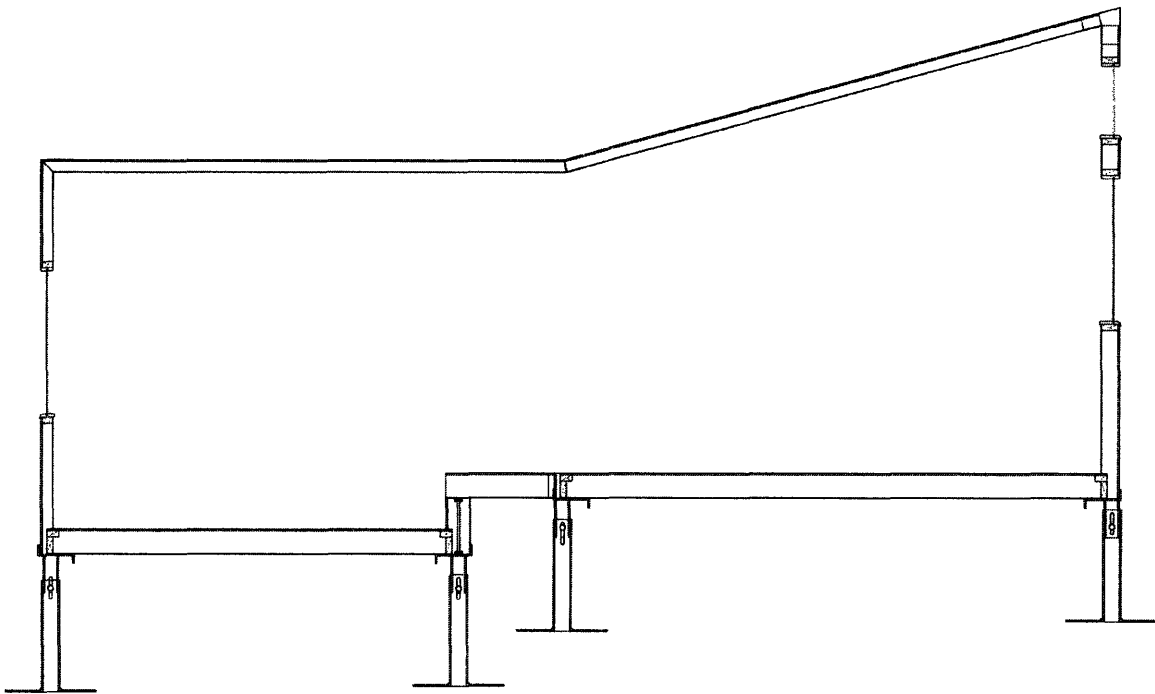
### **Post-Assembly**

As it was not the goal of this thesis to necessarily impinge upon the accepted aesthetics of the vernacular, finish materials – including exterior cladding, interior finishes, doors, windows, and roofing – are not included in this proposed system. Further, the economics of this type of labor (even at this scale) makes it reasonable to hire a professional contractor for such finish work, or simply for the homeowner to do-it-themselves by purchasing the appropriate materials at a home improvement store. The goal of the thesis was not to re-think the *image* of the single-family home, but rather to propose a potential solution to a very serious crises intimately concerning the field of architecture on a much deeper level.

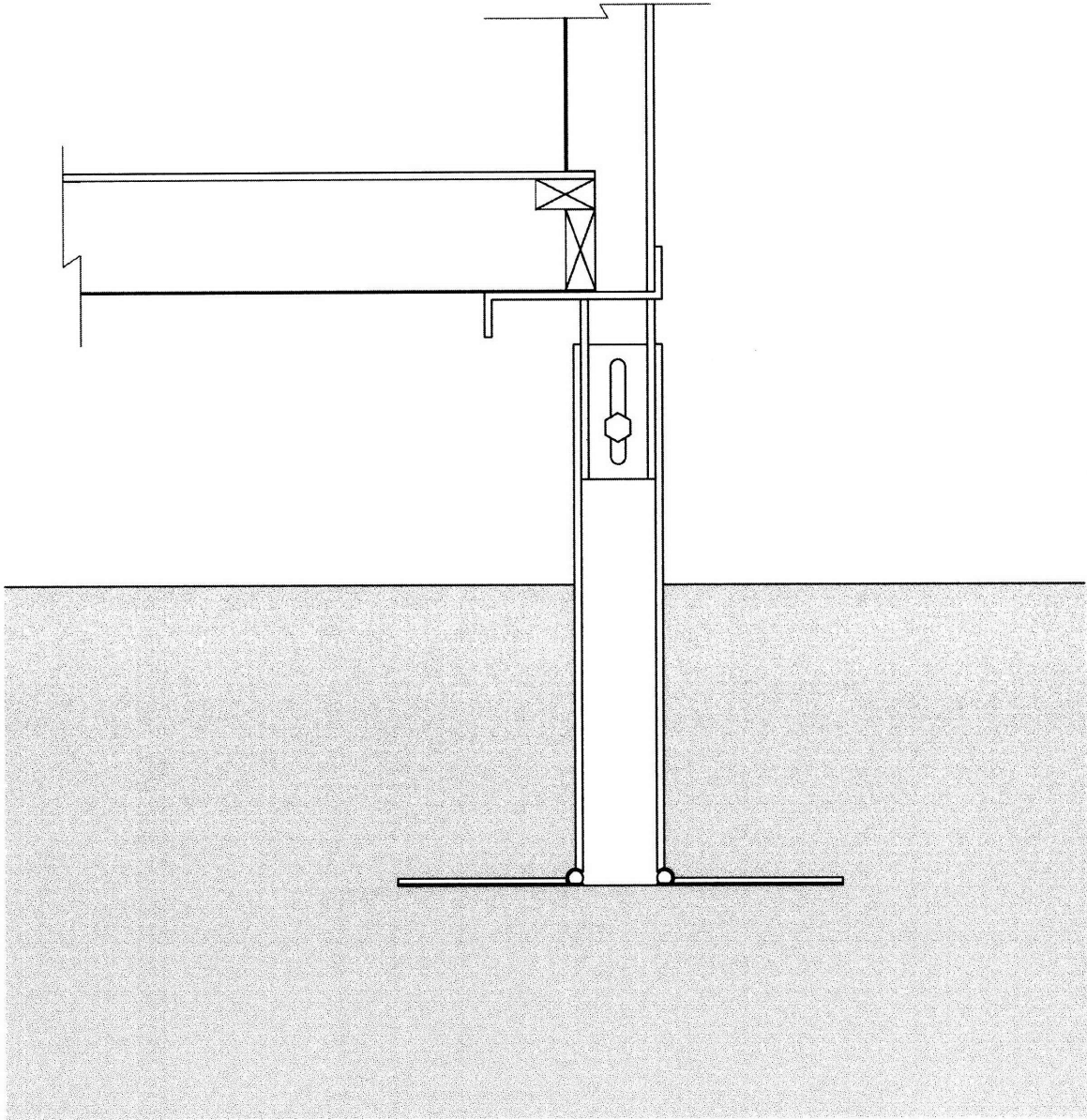




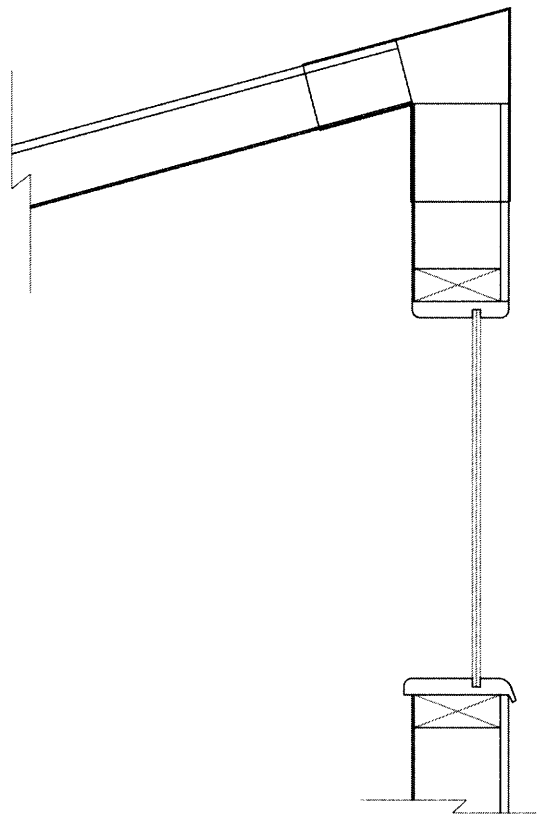
*Figure 30 - Detailed Sectional Axonometric*



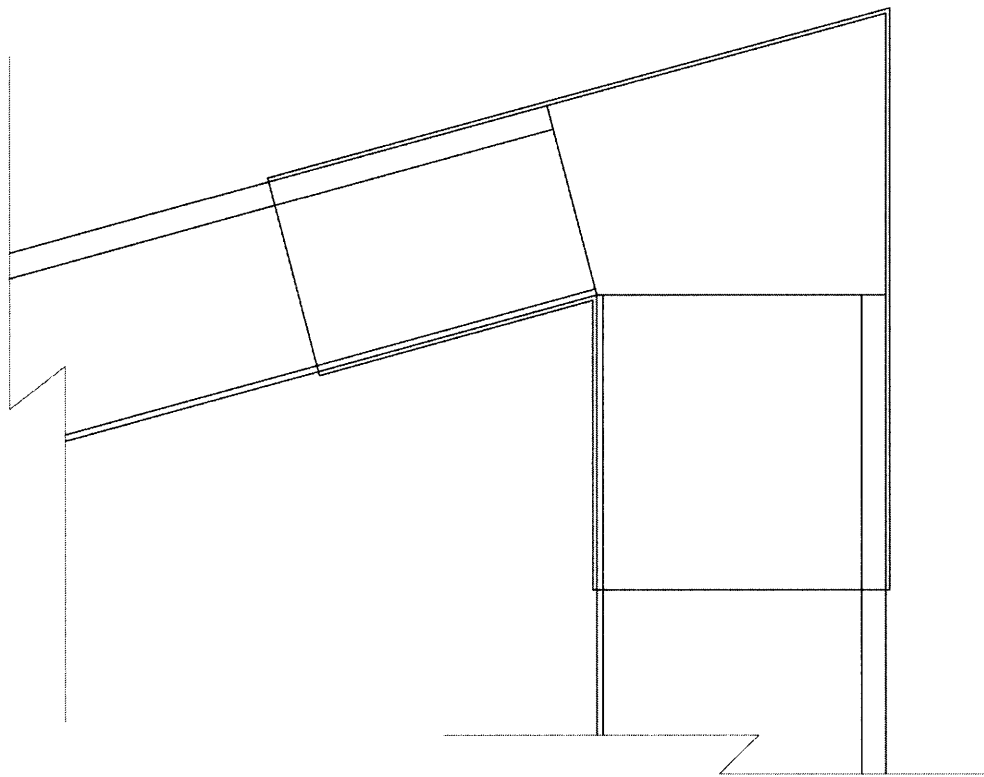
*Figure 31 - Detail Section (Starter Home with Addition)  
(Scale: 1" = 3'-0)*



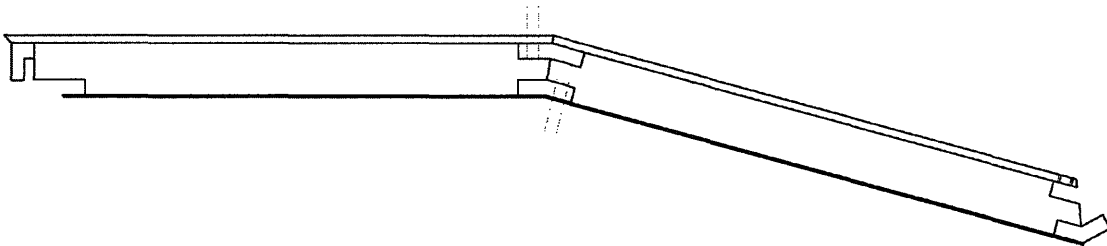
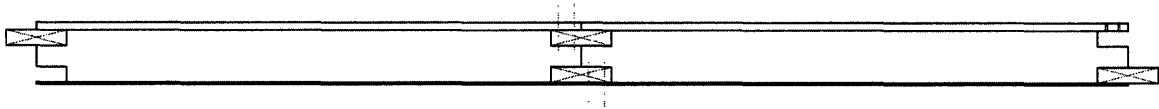
*Figure 32 - Raised Footing Detail  
(Scale: 1" = 1'-0)*



*Figure 33 - Roof Corner Detail  
(Scale: 1" = 1'-0)*



*Figure 34 - Corner Detail*  
*(Scale: 3" = 1'-0)*



*Figure 35 - Panel Joining Details  
(Scale: 1" = 1'-0)*



## SITED DEVELOPMENT PROTOTYPE

### Background

A novel system for bringing homeownership to a new group of Americans (the previously foreclosed) must go beyond the procurement of the product. During the post-war boom of attempted industrialized houses, a reductionist error permeated the industry: that the delivery of the product, whether a kit-of-parts for professional assembly or a fully assembled house, was sufficient to spark innovation in the single-family housing.<sup>209</sup> Industrialized housing companies most often failed not due to technical or design weaknesses, but rather due to the fact that single-family housing is a network, a system, that involves many players and variables; and their industrialized houses did not “jibe” with this system.

*Housing-oriented efforts have usually been based on a technocratically narrow definition of housing as the individual dwelling unit, as a product, as an isolated artifact, as a furniturelike object. However, the quality of housing is affected not only by the design or performance qualities of the unit itself, but much more by the physical, aesthetic, and social qualities of the larger urban context. Such factors as site design, density, functional and social neighborhood mix, availability and quality of services internal to the neighborhood or accessibility to other services, employment, and recreation are at least as decisive determinant of the quality of housing as those of the individual structure. The dwelling unit, the housing process, the neighborhood, and the community framework are inseparable systems.<sup>210</sup>*

Even if customers were willing and able to purchase their product, banks would often not extend mortgages for purchase of a house they could not ascertain would appreciate in value. Even if a bank extended the loan, zoning and neighborhood committees were often reticent, at best, to allow this “aliens” access to land.<sup>211</sup> Land was always available in the laissez-faire domain of proto-rural geographies, but land is also about location and communities, which a single-family home out “in the middle of nowhere” could not provide.<sup>212</sup>

Successful attempts at engaging in a more holistic view of single-family housing were made, and for those innovators success

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<sup>209</sup> See Knerr, *Suburban Steel*, for an indepth discussion of this problem.

<sup>210</sup> Bernhardt, p. 5

<sup>211</sup> See Wallis, *Wheel Estate*, for a lengthy history of this issue.

<sup>212</sup> *Ibid.*

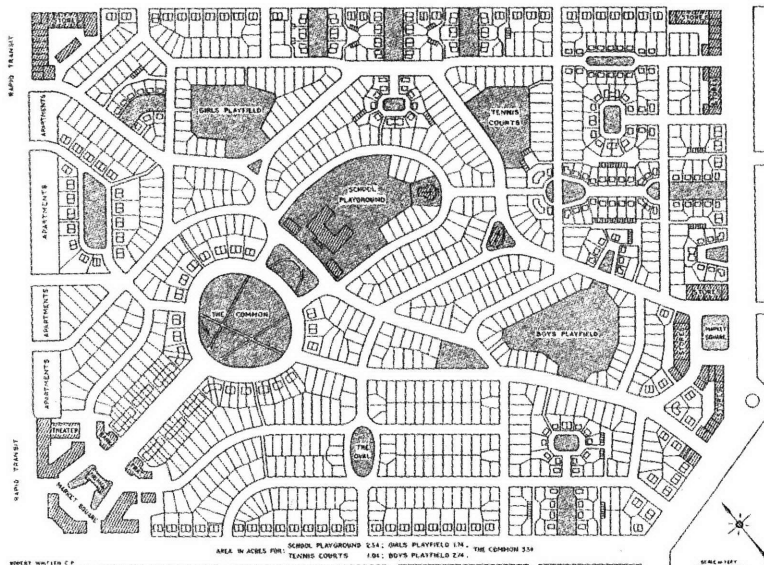
came much closer to a reality. Through business arrangements with mortgage lending banks and an incessant and enticing marketing campaign, the Lustron house was in some cases able to be purchased by bank mortgage and many communities did accept them as neighbors.<sup>213</sup> Levit and Sons, for whom traditional assembly systems prevented problems with mortgage acquisition, continued the 19<sup>th</sup> century tradition of building whole, suburban communities, making the necessary adjustments for affordability.

Most interesting, perhaps, is the network of sites and services promulgated by the manufactured housing ("mobile home") industry.<sup>214</sup> It is fascinating that a housing solution associated at its inception with individual freedom would also lend itself to some of the most aggressive marketing campaigns (read, services) bolstering "community living." Indeed, when banks would not extend mortgages for "trailers" and site-built suburban communities refused to welcome them into their neighborhoods, the industry fought back. Prices were reduced through greater efficiency and special, "personal" loans were created to supplant the need for mortgages. To place their newly purchased manufactured homes, customers found ample "communities" created especially for them, many with all of the amenities of suburban living: stores, post offices, churches, and recreational facilities. (IMAGE) While unfortunate that many banks still refuse to extend mortgage loans for manufactured houses and many communities still refuse to accept them within their towns, mobile home communities continue to propagate and thrive in securing an affordable and agreeable lifestyle of homeownership for many Americans for whom the American Dream would not be possible.

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<sup>213</sup> Knerr, *Suburban Steel*

<sup>214</sup> For an in-depth discussion of the community-building efforts of the mobile home industry, see Wallis, *Wheel Estate*.



**Figure 36 –Mobile Home Neighborhood Plan (1929)**  
*(Clarence A. Perry, Image: Wallis, p. 182)*

## Proposal

This thesis proposes the development of a small but expandable suburban subdivision for the siting of Starter Homes purchased subsequent to the availability of the land. The design-goal of the development is to encourage this market acceptance of the proposed housing system by demonstrating the value of a such mass-customized solution. The development proposal is sited on the north-eastern edge of Las Vegas, Nevada, and consists of three-phases the first of which developed in greater detail.

### Site Selection: Las Vegas

When selecting a site, two criteria were maintained: (1) the geographic location which would be such that a critical mass of foreclosed homeowners would be already present, thus helping to secure a place for this system within the market, and (2) which contain a sufficiently sized area of undeveloped and highly undervalued land not far from an urban center. This second criteria is necessary in that it prevents the separation of its inhabitants from high densities of employment opportunities and, in conjunction with the first criteria, allows its inhabitants to remain near their former, pre-foreclosure communities and social networks.

At the time of this proposal, Las Vegas ranked third in the nation for highest foreclosure rates. In fact, Las Vegas suffers

from the worst general credit crisis in the United States. While the majority of extant “developable” land has already been consumed during the city’s boom in the 1990’s, not far from the city center remain patches of land that, presumably due to their irregular topographical conditions, have been not been developed. This is most likely due to the standardized, mass-produced nature of most American single-family housing. While relatively flat land conditions can be treated as a large, outdoor factory floor (as with Levittown), irregular topographies require a level of variation only feasible within a flexible mass-customized system.

The selected land for development proposal is located 10 miles north-east of the famous Vegas Strip. Because of its higher elevation, the development would not only be located in proximity of the amenities and social networks of the city center, but also benefit from a panoramic view of this American “city of lights.” The general slope of the site topography is at a 11% incline towards the east, further securing the view of the city from almost all plot on the development even as the community grows in density.

The specific area on the site was chosen because of its adjacency to existing infrastructure. The parcel is bordered along the north<sup>215</sup> and west<sup>216</sup> by extant roads, reducing necessary initial capital investment while immediately securing connectivity of the new development to the existing fabric of the city. Along the north-south access, the development is proposed to extend the entire length of the undeveloped site; however, development must be curtailed eastbound due to drastically increasing topographical slope at this point.

## **Development Plan**

It is proposed that development of the site occur in three phases, again to minimize initial capital investment towards the goal of expediency. The first phase is to comprise the northern third of the site, taking advantage of the existing east-west running road, East Owens Avenue. As road running against the slope of a site are the most expensive to develop, this extant infrastructure will uniquely provide the east-west running access to the site. Less expensive north-south running roads along the slope will trickle down from East Owens Avenue to the southern edge of the first phase of development.

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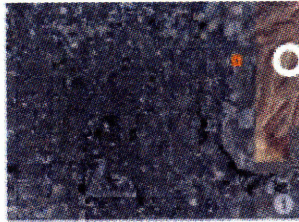
<sup>215</sup> East Owens Avenue

<sup>216</sup> Los Filez Street

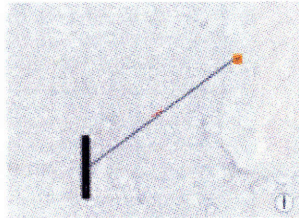
In total, six new, north-south running roads are proposed. The form of the roads are such that they run parallel to the fluctuating slope of the site, however efforts are to be taken to maintain equal distancing between roads. By organizing the roads thus, erratic topographical conditions are prevented from occurring on individual plots, and plot sizes maintain equal square footage where possible. The goal is to maintain an equal grid of subdivisions so as to promote site selection, by potential residents, based on design-related criteria (orientation, views, topography) rather than crude selection by area. Rather than driven by an equalizing impulse between plots, this decision was made towards the promotion of do-it-yourself design thinking from the very onset of the process.

The shape and dimensions of the individual subdivision plots are also designed towards the goal of promoting a variety of spatial conditions at the development scale and do-it-yourself design thinking on each individual plot. The Starter Homes themselves cannot be placed against the slope, due to their single-level design, and thus must be oriented (in this prototypical development) along the shorter, ostensibly north-south bound axis of each plot. This does not, however, create a homogenous architectural landscape as the erratic topography of the development ensures that exact orientation of each Starter Home conforms to the local direction of the topography.

More than designing into the development variation, this plot layout also acts in a manner similar to the Clay Manipulation design tool described earlier. Each plot is 60ft along the topography (north-south axis) and 100ft against the slope. This orientation is optimal for maximizing the amount of plots on the parcel while ensuring ample spacing between homes for the maintenance of views towards the cityscape to the west. Further, as the necessary orientation of the Starter Home allows for only ten feet between each Starter Home at its plot boundary along the topography (ostensibly north-south), future expansion of the home must occur against the slope of each plot, thus actively nudging the do-it-yourself designer towards engaging the relationship between the site and the sectional layout of the constantly evolving home. Thus, while once again helping to direct the homeowner towards a open-minded rethinking of the spatial interpretation of the needs and desires, the sectional shifts in part resulting from plot-specific topographical conditions will further act to erode the homogeneity of development mass-produced Starter Homes, as witnessed in the evolution of Levittown, into a truly heterogeneous (sub)urban condition of inhabitant-specific and site-specific dwellings.



Prototype development to be located in northeast fifth of Las Vegas, Nevada.



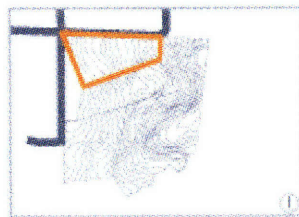
Development is only 10 miles from the strip, but, due to the irregular nature of the site, is undesirable for typical cookie-cutter development, and thus presumed to be highly underutilized.



While right at the border of medium to high density middle-class suburban development, the site itself now stands as a desert amidst a city.



The western portion is deemed too intractable for rationalized development.



The site is subdivided externally into three development phases. The northern most phase is chosen to benefit from the extent uphill road to the north.

**Figure 37 - Phase One Site Selection**



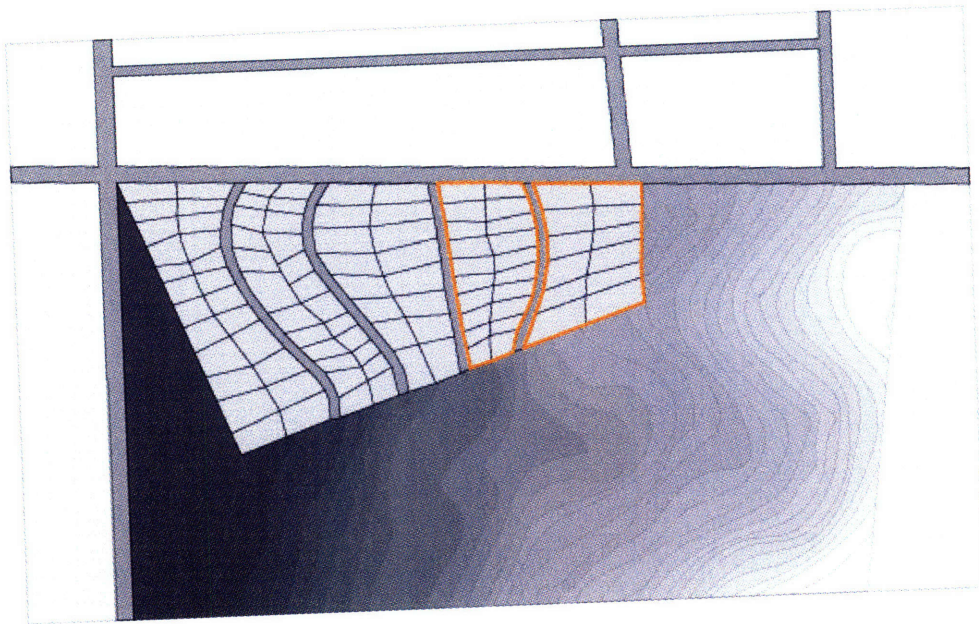


Figure 38 - Phase One Plot Plan<sup>217</sup>  
 (See highlighted detail below.)

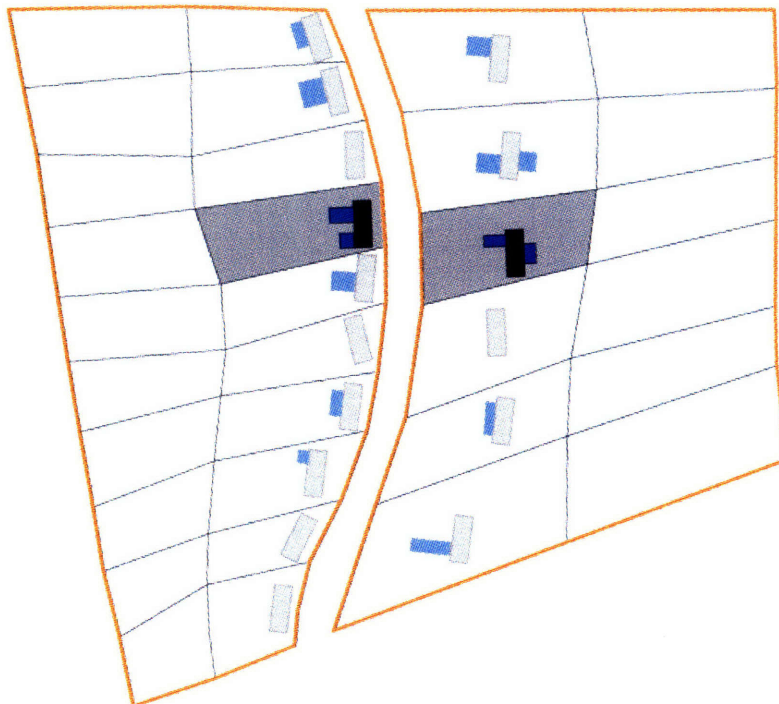
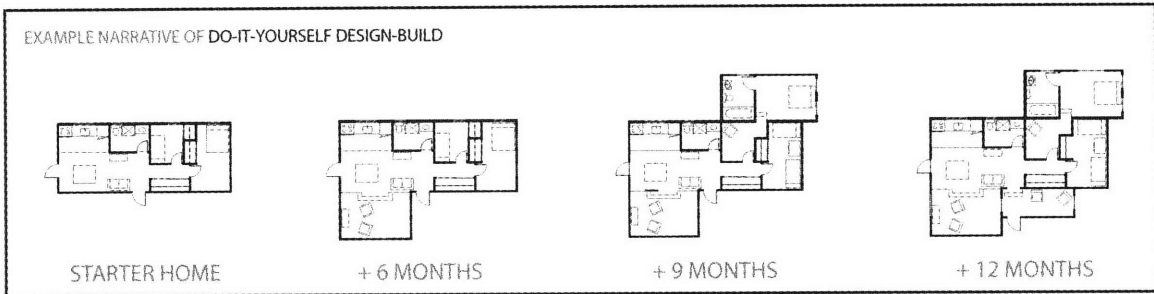
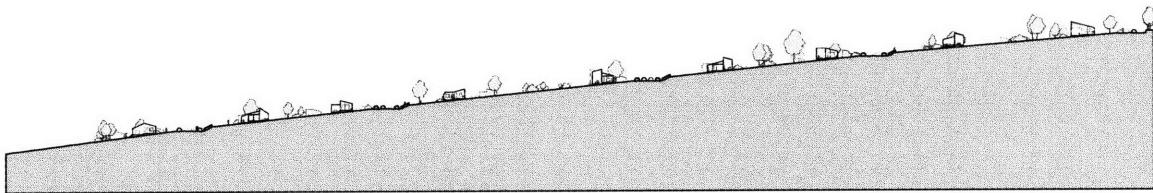


Figure 39 - Phase One Plot Plan Detail<sup>218</sup>

<sup>217</sup> Graphic by Viktorija Abolina, MIT  
<sup>218</sup> Graphic by Viktorija Abolina, MIT



*Figure 40 - Sample Plan Evolution*



*Figure 41 - Prototypical Development (Section)*

## **CONCLUSION**

The design of a viable, holistic system for single-family housing involves a very large number of issues, factors, and variables. While a complete proposal to return homeownership to foreclosed Americans goes beyond the scope of this thesis, the hope is that the above schematic outlines some of the major issues involved and presents a possible direction towards addressing these issues. It is the responsibility of the architecture profession, in the opinion of this author, to tackle such issues from a holistic point of view that considers the future of housing and the role that architects can play in directing this future.

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