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# Contour Crafting: A New Automated Construction Technology and its Benefits to the Environment

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## Abstract
Contour Crafting (CC) is a layered fabrication technology using robotic arms and extrusion nozzels, developed at the University of Southern California. The potential impact of CC in construction became evident after successful experimentation with various construction materials such as clay, plaster and concrete. The technology is at a stage where complex shapes such as walls and domes have been constructed. The objective of this paper is to quantify the comparative life-cycle embodied energy and $CO_2$ emissions of a concrete frame house built by two different methods: the automated CC technology and a standard manual construction using Concrete Masonry Unit (CMU). Our comparative life-cycle models (LCA) indicate that CC results in a reduction of 72% in total $CO_2$ emission compared to the manual CMU construction method. Also, the total embodied energy of a CC building is reduced by 37% over the CMU construction method. Our calculations also indicate a ratio of 5 to 1 reduction in solid waste generated by CC compared to CMU on a life-cycle basis. LCA model assumptions and future research directions are discussed

## Keywords
Construction automation, Contour crafting, Environmental impacts, Embedded energy, Carbon dioxide

## 1. Introduction

Contour Crafting (CC) was first envisioned as a rapid prototyping process aimed at fabrication of large scale parts (Khoshnevis, 1999, 2004; Khoshnevis and Bekey, 2003). CC simultaneously uses computer controlled extrusion and troweling to achieve smooth and accurate free-form surfaces.

The process smoothly forms external surfaces of the object by constraining the extruded flow by a solid trowel surface. The orientation of the trowels is dynamically controlled to conform to the slope of surface features (see Figure 1). Thus, no matter what the desired surface is, the fabricated surface is always a ruled surface because the side trowel always forms a tangent plane to the surface that it forms. Note that the side trowel can change its orientation through deflection during fabrication. If the side trowel changes its orientation then the bottom base curve changes accordingly, but the ruling remains the same.

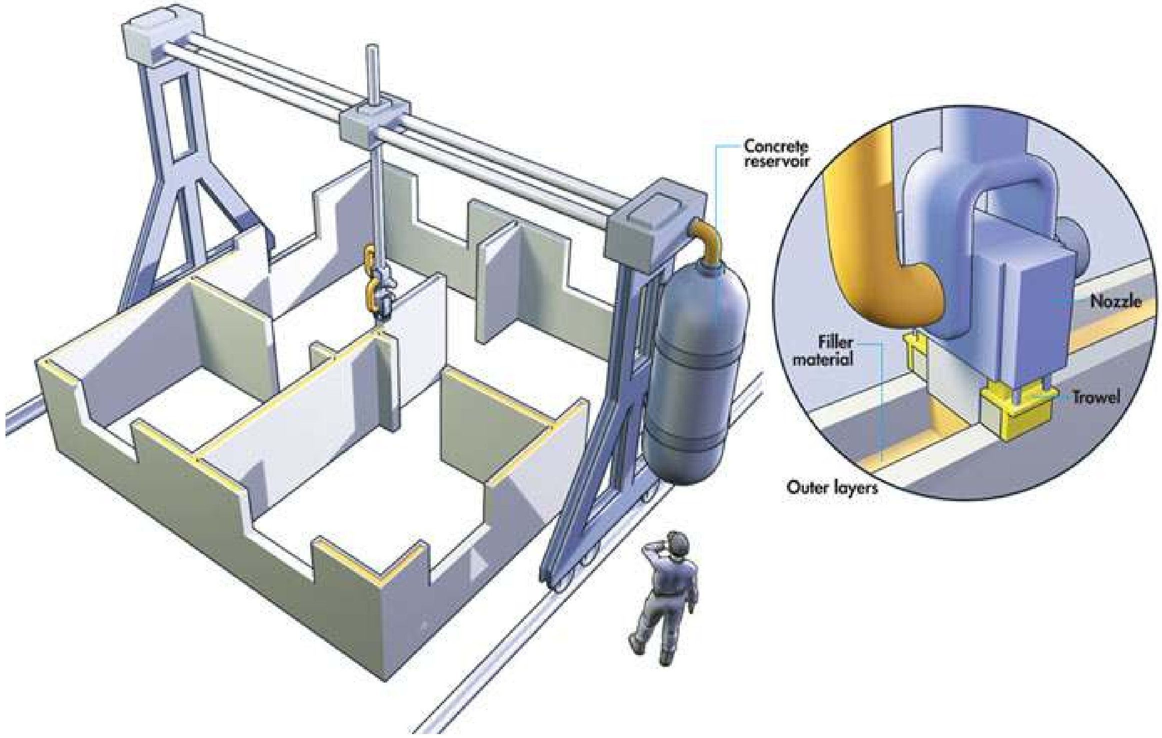


**Figure 1: A Depiction of Contour Crafting System Building a House**

The key feature of CC is the use of trowels in conjunction with a robotic extrusion system. Artists and craftsmen have effectively used simple tools such as trowels, blades, sculpturing knives, and putty knives for forming materials in paste form since ancient times. However, despite the progress in process mechanization with computer numerical control and robotics, the primary method of using these simple but powerful tools is still manual, with the consequent result that their use is limited to model building and plaster work in construction. In CC, computer control is used to take advantage of the superior surface forming capability of troweling to create smooth and accurate, planar and free-form surfaces. CC is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core. As shown in Figure 1, the CC nozzle can deliver paste materials and is equipped with a trowel. As the material is extruded, the traversal of the trowel creates smooth outer surfaces on the layer. The nozzle or the trowel can be deflected to create non-orthogonal surfaces. The extrusion process builds only the outside edges (rims) of each layer of the object. After complete extrusion of each closed section of a given layer, if needed, filler material can be concurrently poured to fill the area defined by the extruded rims, while new rims are built by the troweling method. Several animations and videos of the CC process may be viewed at www.ContourCrafting.org. Some of the animations show the application of the process to very large scale structures such as buildings.

Extensive experiments have been conducted to optimize the CC process to produce a variety of 2.5D and 3D parts with square, convex, and concave features, some filled with concrete (see Figure 2). More recently a CC machine was designed that is capable of building full scale wall sections out of conventional concrete (see Figure 3). A number of non-traditional construction projects are being tested using CC as well. For example, CC is being currently tested to build habitat on the moon and Mars (see Figure 4 for dome structures constructed with lunar regolith simulant material at NASA Marshall).

However, as CC is being considered for large scale applications in construction industry, questions have been raised as to its environmental impacts relative to other standard construction techniques.

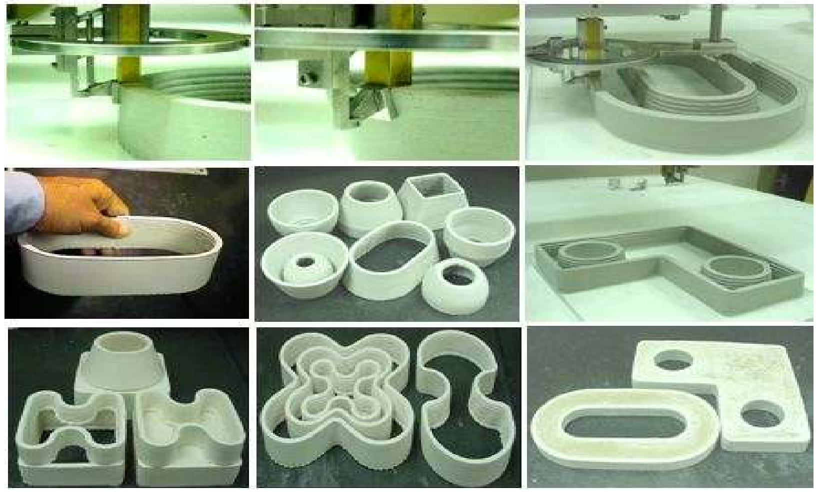

**Figure 2: CC in Operation (First Row) and Representative 2.5D and 3D Concrete Shapes**

**Figure 3: Full-Scale Concrete Walls Built by CC**

**Figure 4: Dome Structures Built using CC at NASA Marshall Space Flight Center**

The question is an important one since buildings account for 40% of material and energy use and 33% of $CO_2$ emissions (Keazer and Ridgeway, 2008). And, buildings result in 136 million tons of construction and demolition waste in the U.S. alone. Nevertheless, new construction techniques have created significant opportunities for environmental impact research. Recent market data show that top market drivers representing the growing strength of the green building marketplace include market transformation, market demand and client demand (MHC, 2009). Green building approaches may include new sustainable materials (e.g., the use of recycled contents in new products), application of non-traditional materials that have less recycled content (e.g., geopolymers), new construction techniques that reduce waste, and innovations in the management and scheduling of projects.

## 2. Life-Cycle Environmental Impact Analysis

One measure of success for the application of automation technology to construction is its ability to reduce the building's total environmental impact on a life-cycle basis. In order to make any claim in the direction of environmental preference, the comparison should be made using similar functional performances. That is, a house built with an automated approach should be the same in terms of design functionality as one build with a manual approach, i.e., the same functional unit.

The life-cycle environmental impacts of buildings are calculated through the phases of: materials extraction and manufacturing, transportation, use and the end-of-life demolition and disposal. A widely used modeling approach for such multi-phase assessment is Life-Cycle Assessment (LCA) which was standardized by ISO 14000 and SETAC in 1990s. LCA is most aptly described as a *systematic methodology* for the identification of environmental impacts and consequences, over an appropriately defined life cycle, and comprised of certain specific elements and assumptions.

## 3. House Design Characteristics and LCA Assumptions

The CC design was a simple square design with features that make automation easy with a single cantilever robot. For CMU, a standard design was selected from the literature, currently used in the market for concrete block construction. In terms of basic materials, CMU uses a standard masonry block unit with Portland cement as the primary material. The CC house uses ready-mix concrete as the main construction material. Other assumptions and exclusions are listed below.

To reduce the LCA complexity, the following impacts were not addressed in this study:

- Site location impacts on the surrounding ecosystem
- Energy/materials related to landscaping, irrigation, etc.
- Non-structural items inside the house
- Embodied energy of the raw material production
- Minor differences in house shape design due to the surface to volume ratio

Also, the impacts from the following sources and processes were not included in this comparative study because they were assumed to have equal life-cycle impacts for both approaches:

- Use phase energy consumption (heating, cooling, lighting, electricity and power outlet)
- Materials maintenance and improvement
- Building demolition after its useful life
- Recycling of materials and transportation to landfill

The major design specifications for each house are summarized in Table 1 below.

**Table 1: LCA Functional Unit and Design Characteristics for CMU[*] and CC**

| *Characteristic* | *CMU* | *CC* |
|---|---|---|
| Single-family dwelling type | 1 story bungalow slab-on-grade | |
| Floor area | 2,153 $ft^2$ (200 $m^2$) [*] | |
| Foundation (footing and slab) | 3000 psi (20 MPa) concrete, Unit weight, 2,320 $kg/m^3$ [**] | |
| Foundation walls | None | |
| Main floor | Supported slab-on-grade (no basement) | |
| Exterior walls | Concrete block | Ready-mix concrete |
| Partition walls | 2"x4" wood studs @ 16" (400mm) o/c, No sheathing | Ready-mix concrete |
| Roof | Light frame wood trusses with plywood sheathing | Strong steel beams with Plexiglas® underneath covered by concrete |

[*] *from Meil, 2002*
[**] *from Marceau et al., 2002*

For the purpose of this study, BEES 4.0 database was used extensively for the CMU approach (Building for Environmental and Economic Sustainability from National Institute for Standards Technology, Office of Applied Economics). One limitation of BEES is that it does not contain the emission and embodied energy for the production phase. We have manually extracted and calculated this information from the Portland Cement Association (PCA) life-cycle inventory database (Marceau et al., 2002). To increase data reliability and reduce computational error, we have used the house characteristics already modeled by CORRIM (Consortium for Research on Renewable Industrial Materials) in "Environmental Impacts of a Single Family Building Shell-From Harvest to Construction". The DOE's National Renewable Energy Laboratory database was also used for data unavailable elsewhere.

To begin the analysis, a Bill of Materials was generated for each construction method. Based on each material composition and amounts, raw material inputs were calculated. Using the available life-cycle databases mentioned above, we generated a set of tables for the embodied energy and $CO_2$ emissions for each life-cycle phase.

## 4. Results

The summary of $CO_2$ emissions and embodied energies for CMU and CC by phase of activities are given in Tables 2 and 3.

**Table 2: Summary of $CO_2$ Emissions (kg) by Life-Cycle Phase**

| *Phase* | *CMU* | *CC* |
|---|---|---|
| Extraction, Transportation & Manufacturing (ETM) | 1.31E+05 | 1.54E+05 |
| To and On-site Transportation (TOT) | 4.57E+05 | 9.87E+03 |
| On-site Construction (OC) | 5.24E+03 | 1.46E+02 |
| **Total** | **5.93E+05** | **1.64E+05** |

**Table 3: Summary of Embodied Energy (GJ) by Life-Cycle Phase**

| *Phase* | *CMU* | *CC* |
|---|---|---|
| Extraction, Transportation & Manufacturing (ETM) | 7.92E+02 | 1.29E+03 |
| To and On-site Transportation (TOT) | 2.90E+03 | 1.18E+03 |
| On-site Construction (OC) | 2.70E+02 | 8.64E-01 |
| **Total** | **3.96E+03** | **2.48E+03** |

As these tables indicate, *CC has a reduction of 72% in the total $CO_2$ emissions compared to CMU. The total life-cycle embodied energy of a CC building is reduced by 37% over the CMU construction method.*

Table 4 shows the solid wastes for CC and CMU for the manufacturing and construction phases. The solid wastes produced in the other phases were ignored in this calculation because they were the same for both construction methods. The CMU values were derived from CORRIM reports directly. The concrete solid wastes for CC were calculated in proportion to the waste ratio of concrete block to ready-mix using PCA values. The average solid waste is assumed to be 24 kg/m$^3$ for ready-mix and 66 kg/m$^3$ for concrete masonry, based on the data from Marceau *et al*., (2007). As for the steel waste, the values are directly derived from NREL LCI database (averaged of 19.8 kg/1000lbs) and calculated for the total amount of steel used in each phase for robot and ceiling T-beam manufacturing wastes.

**Table 4: Solid Wastes (kg) by Manufacturing and Construction Phases**

| *Phase* | *CMU*[*] | *CC* |
|---|---|---|
| *Manufacturing* | | |
| Bark/wood waste | 137.21 | 0.00 |
| Concrete solid waste | 1,684.21 | 606.32[**] |
| Blast furnace dust | 51.60 | 51.60 |
| Blast Furnace Slag | 251.01 | 251.01 |
| Steel waste | 0.00 | 404.95[***] |
| Other solid waste | 799.67 | 161.12 |
| Sub-Total | 2,923.70 | 1,475.00 |
| *Construction* | | |
| Bark/wood waste | 795.97 | 0 |
| Concrete solid waste | 4,249.81 | 0 |
| Blast furnace slag | 0.00 | 0 |
| Blast furnace dust | 0.00 | 0 |
| Steel waste | 1.59 | 0 |
| Other solid waste | 0.01 | 0 |
| Sub-Total | 5,047.38 | 0 |
| **Total** | **7,971.08** | **1,475.00** |

[*] *from Meil et al., 2002*
[**] *from Marceau et al., 2002*
[***] *from NREL database*

Based on this analysis, *CC produces 81.5% less total solid waste compared to CMU, during its material manufacturing and on-site construction phases.*

We also added a set of analyses to model two environmentally friendly construction materials as substitutes for cement: slag cement and geoplymer. Overall, the CC method was significantly less impactful, reducing the $CO_2$ emission by 76% for slag cement substitution, and 88% for geopolymer substitution.

Finally we explored the potential of CC to reduce $CO_2$ emission and energy usage for building cement walls, e.g., highway walls for noise and pollution abatement. This analysis was conducted on the basis of building a square foot of surface using CMU and CC approaches. In order to do this, we already had the volumes of concrete for CMU and CC which were 25,333 and 25,777 $ft^3$ respectively. This volume was converted to a square foot of surface for each method. This resulted in 13.58 kg of $CO_2$ per square foot of wall for the CMU method. Using the same approach, we calculated the total energy per square foot of the wall to be 0.08 GJ for the CMU method. On the other hand, for CC method, we found 3.11 kg of $CO_2$ and 0.04 GJ of energy per square foot of the wall, respectively. Therefore, for a square foot of wall construction, CC reduced the total life-cycle $CO_2$ by 77% and reduced the total energy by 50% compared to CMU wall construction method.

## 5. Conclusion

It appears that the CC construction technology has significant advantage over the current CMU approach in terms of $CO_2$ emissions and energy use on a comparative life-cycle basis. In addition, a large amount of waste generated by this industry would be of less issue if CC is implemented in its full automation potential. The environmental advantages of CC is a result of less total material use, less total energy required for all construction activities, less transportation of material, equipment, and labor, and lower material and energy waste during construction. Local, national and global trends toward reductions in GHG energy use (e.g., passage of the California's Assembly Bill 32) will strengthen the position of this new technology in the future.

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