PREFABRICATION DEPTH

PROBLEM STATEMENT

Prefabrication is an incredibly useful tool available to the construction industry today. Unfortunately, it has a stigma attached to it that makes some owners cringe when they hear the word. While prefabrication has been around for hundreds of years, it is still very misunderstood. Owners and designers need a better basis for making the decision to go prefab.

GOAL

Through this prefabrication research I wish to determine the origins of prefabrication and what has kept the concept going for so many years. This depth study will identify the advantages and disadvantages to prefabrication and describe a model to help owners make the decision of using prefabricated materials. Finally, since the theme of this thesis project is the building façade, I will research and compare various types of precast brick panels systems. This will ultimately assist in selecting a specific product to be used on the Wisconsin Place project.

RESEARCH STEPS

1. Gather research on the history of prefabrication.
2. Research methods for deciding to choose prefabrication.
3. Identify the advantages and disadvantages of prefabrication.
4. Research prefabricated facades and compare products.
5. Research new technology for prefabricated brick facades.

TOOLS

1. Journal of Construction Engineering and Management
2. Journal of Aerospace Engineering
3. PACE conference
4. KPFF Consulting Engineers
5. ASCE Journal of Architectural Engineering
6. Penn State Libraries

EXPECTED OUTCOME

The results of this prefabrication research should be further enlightenment as to why the decision to implement prefabricated items is such a complex one and to establish a fixed method to make the decision. After comparing different precast brick panel systems I would like to select one to use in my Analysis 1 precast façade implementation.

History

Prefabrication has been around for many years, but the concept and practices are still evolving. Andreas Palladio standardized architectural forms like column proportions and stair arrangements in the 16th century as a response to the high demand for palaces and villas of similar size and structure. Following World War I in Europe, prefabricated houses replaced the ones that were destroyed in the fighting. The Baby Boomers of World War II once again sparked the need for cheap and fast housing in the US when they returned home to start families. It is evident that there has been a continual need for prefabrication around the world for centuries, but the need is ever changing with the times and new technology.

The concept behind prefabrication in construction is that large units of a building can be pre-assembled in factories or warehouses and delivered to site ready-to-install. A key factor in optimizing prefabrication lies in the ability to break a task down into smaller components, like an assembly line. By combining smaller parts into a whole, larger elements can be incorporated into the building system, reducing schedule time and site congestion.

This depth focuses specifically on prefabricated building facades and compares different systems and methodologies. It addresses why, after thousands of years, people are still hesitant to use prefabricated materials. My research will also include some tips, even a decision guide, to determining whether or not a project should utilize prefabrication. I will compare different precast systems and look into some new technologies that have not yet broken out onto the market.

Advantages and Disadvantages

On any given project, an owner is seeking high levels of value, safety, quality, productivity, and performance. Prefabricated items can satisfy all of these requirements as long as the project team is willing to invest the extra time and money into planning for it. On a project with adverse site conditions prefabrication would be beneficial. For example, if a building is being constructed in an area with very cold climate, it would be extremely difficult to maintain a steady concrete pour schedule for the structural system. Concrete requires a certain window of temperatures to cure, so the project would be delayed on the days when it is too cold to pour slabs.

Prefabrication is an effective solution for a demanding schedule, as it is faster to attach larger pieces to a building. Projects looking to reduce costs can realize savings in a shorter schedule. Complex designs sometimes dictate prefabrication. Intricate elements are better assembled off-site, where quality control can be more closely monitored.

In many cases, owners and designers alike rule out the idea of prefabrication on a project because it requires much more careful planning and execution. Prefabrication is also a decision that needs to be made upfront so that proper design and coordination can be ensured by the architect and general contractor. Owners are hesitant to commit to prefabrication so early in the design stage.

Some other drawbacks to prefabrication are a potentially higher upfront cost as well as transportation cost. If a factory is 50 miles away the contractor/owner needs to consider how the materials will arrive to the site. Besides the cost of gas, physical limitations like low underpasses or truck weight limits could prevent materials from travelling to their desired location. Lack of flexibility in design also detracts buyers from prefabricated products. This is not so true today, but in the past, prefabrication was strongly associated with a standard vanilla box. Maintaining a sound building envelope is another major concern of the owner, architect, and general contractor. Since assembling a precast façade is like putting a puzzle together, there will be many tiny cracks between the connections. This affects the acoustical, thermal, and water-resistant properties of the exterior skin. Consideration must be given to sealants, insulation, and vapor barriers to make a precast building just as good as a stick-built one.

Prefabrication requires more engineering, more materials, and additional work to assemble materials. The cost is usually higher than ground-up construction, and lead times are a concern for all those involved with the design process. But if these constraints are addressed early enough in the design process prefabrication can be a feasible option.

Computer Software & PPMOF

In a paper published in the Journal of Construction Engineering and Management, a team of one graduate student, one project engineer, and three professors discuss the factors influencing the decision of prefabrication use. The term PPMOF is coined as 'Prefabrication, Preassembly, Modularization, Off-site fabrication.' It was noted that the use of prefabrication has nearly doubled over the past 15 years, but the industry has not fully recognized the potential improvements that PPMOF has to offer. The paper stresses that prefabrication is something that should be directly applied to certain areas of a project, like the façade or furniture. It is not something that can be applied across the board as a percentage. In this way, prefabrication is still misunderstood.

The researchers explain about MODEX, a DOS-based software system used to determine the feasibility of implementing modular technology. The program prompts the user for project information, existing conditions, etc., and provides a cost analysis as well as projected schedule. Form this output, the user can determine the feasibility of utilizing prefabrication on their project. Results of testing concluded that the program's recommendation matched that of industry professionals 91% of the time.

Neuromodex is a more advanced software tool that is able to handle inexact and incomplete inputs. Typically, at the beginning of a construction project, there are many holes in design that the architect fills in later. This program is a step up from the original MODEX that required more exact data. It also uses expertise input by humans to rationalize the use of PPMOF. Neuromodex extends beyond basic known facts and exercises higher level reasoning. However, the program is still not aware of the rules that motivate its decision-making.

In 2000, a prefabrication study was conducted to see how many industry members used either MODEX or Neuromodex as a decision tool for modularization. The results of surveying 29 construction professionals showed that the use of these two computer programs has increased from 14% to 27% over the past 15 years. The areas of significant growth included equipment, instrumentation, ironwork, mechanical piping, and structural assembly. The survey determined that the top driving factors for PPMOF were cost, schedule, and workforce issues like lack of labor. Some of the barriers to prefabrication were additional planning, increased transportation difficulties, greater inflexibility, and more advanced procurement requirements.

CII Decision Guide

In order to successfully implement prefabrication on a project, managers need a clear and decisive method for analysis, and a team of two researchers, Cigolini and Casteliano (CII), have been collaborating since 2002 to develop the following evaluation model. It looks at the cost variance between stick-built and modular construction and tries to bridge the gap between the economic analysis of MODEX and the actual estimation process.

To come to a conclusion, CII visited nine industrial sites and were able to identify several commonalities between all nine projects. One was that prefabrication complexity determines decision timing. If the entire project is being modularized, precise decisions had to be made during pre-project planning. If less critical prefabricated elements were to be used, decisions could wait until the detailed design phase. Most of the companies took advantage of weekly meetings between disciplines to ensure proper communication.

Analysis of labor differentials associated with moving the activity from field to factory were also considered. Managers examined differences in wage rates, productivity, project risk, equipment, and overhead costs related to labor.

Finally, transportation was another major issue that was investigated for prefabrication. One company maintained a specific department that dealt with transportation planning. Another company required that prefabricated products be tested before they are shipped to ensure they can withstand the stresses of travelling.

I was interested to learn that these nine companies considered prefabrication a form of outsourcing, or sending work to a separate location where it can be accomplished best and cheapest due to economies of scale. I usually identify outsourcing as sending work overseas to be completed. But outsourcing exists within the United States as well. I think there are many advantages to this, some being promoting homeland economic growth and lowering shipping costs.

The figure below shows a decision framework chart to help industry members think completely through the prefabrication design process. Levels I and II are meant to walk managers through primary drivers and roadblocks to prefabrication. Strategic I is a business planning screening tool that evaluates the feasibility of PPMOF. Level II is to be used during pre-project planning and assumes more project knowledge like site location, labor, permitting, and infrastructure can be provided. The Tactical Level Analysis is the final level that focuses on the bottom line: cost. It is recommended that this step be performed during the conceptual design phase when quantities are known.

Activity	Project Life Cycle Through Construction				
	Business planning	Conceptual planning	Conceptual design[a]	Detailed design[b]	Construction
1. Complete Strategic Level I analysis	◆				
2. Accumulate preliminary information including plot plan, flow sheets, and equipment lists	▬▬	▬			
3. Complete Strategic Level II analysis		◆			
4. Develop alternatives for PPMOF use		▬▬	▬		
5. Complete Tactical Level analysis (I)[c]			◆		
6. Refine estimate and quantities			▬▬	▬▬	
7. Complete Tactical Level analysis (II)[d]				◆	

[a]At start of conceptual design: estimate approximately ±30%, project team has plot plan, flow sheets, and equipment lists
[b]At start of detailed design: estimate approximately ±10%, quantities determined
[c]For decisions on level of modularization and complex preassembly
[d]For decisions on level of simple preassembly and prefabrication

Decision timing map for prefabrication, preassembly, modularization, and off-site fabrication

The extent to which the decision framework must be used depends a lot on the company and how much they want to justify PPMOF use. The nice thing about this guide is that it can be utilized to the extreme or as a precursory analysis of prefabrication.

The evaluation tools designed by the CII team allow managers to rank the relative importance of various factors such as cost, schedule, safety, design, and transportation. An example of Levels I and II are shown below.

Decision Support for
Prefabrication, Preassembly, Modularization, and Off-site Fabrication

Strategic Level I Evaluation Evaluation Date:

Project Name: Evaluator:

Answer questions based on knowledge of the project under consideration. Follow the interpretation and save the results for later use, as they can be combined with the results of later evaluations for the final decisions regarding PPMOF.

Section	Question	Impact on PPMOF
Schedule	Are their significant constraints or requirements for the project schedule? PPMOF may help to meet schedule constraints such as outage duration and time to market or decision needs.	Yes Maybe No
Labor	Is there a lack of good local labor available in the project area? PPMOF may help by moving work to areas with adequate labor.	Yes Maybe No
Safety	Is there an opportunity to decrease safety risks by using PPMOF? PPMOF may be able to relocate work to less hazardous environments such as ground level or controlled climates.	Yes Maybe No
Environmental, Legal and Regulatory	Are there significant environmental, legal and/or regulatory considerations that may constrain the project? PPMOF may help to alleviate constraints by allowing parallel work while such issues are handled.	Yes Maybe No
Site Attributes	Are there significant site attributes such as extreme weather or lack of infrastructure that may impact project performance? PPMOF can potentially relocate work to more favorable conditions.	Yes Maybe No
Site Access	Do available routes and lifting paths allow using modules with the dimensions set by truck, rail, or barge shipment? Using the largest possible modules increases the benefits of PPMOF.	Yes Maybe No

Strategic Level I Evaluation

CII Strategic Decision Tool for PPMOF
(Prefabrication, Preassembly, Modularization, and Off-site Fabrication)

Reports of Extremes for Strategic Level II Evaluation

Project Name: Fill out on Welcome page | **Data Date:** Fill out on Welcome page
Evaluator: Fill out on Welcome page | **Evaluation Date:** June 19, 2002

Factors Most Strongly Supporting PPMOF

Rank	Raw Score	Weighted Score	Factor	Category	Question No.
1	5	1.00	Shortened schedules	Schedule	1
1	5	1.00	Timing of environmental or other project permitting	Schedule	5
2	5	0.60	Local, regional, or national labor availability	Labor	3
3	5	0.40	Reductions in insurance costs	Safety	6
3	5	0.40	Requirement for early "freezing" of design	Design	2
3	2	0.40	Late business decisions	Schedule	3
3	2	0.40	Early startup benefits	Schedule	4
3	2	0.40	Rewards for early project completion	Schedule	9
4	2	0.32	Requirements to meet new regulatory or other imposed requirements	Cost	3
4	2	0.32	Future reuse value	Cost	4

To save and print your evaluation results, please go to the Final Score (Summary) sheet and press the "Save" and "Print" buttons. | **Final Score** | **Final Score Interpretation**

Strategic Level II Evaluation

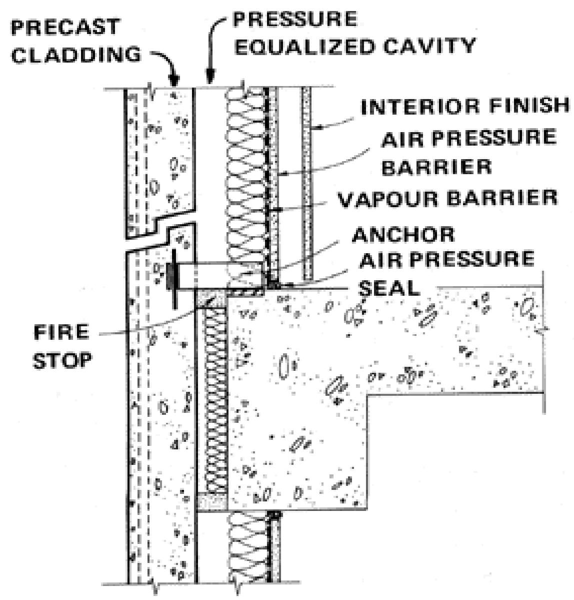
The CII tool seems to be a very practical and useful aid for managers because it facilitates a design process dialogue between all disciplines, forces people to prioritize their decisions, is easily maintained, and clearly identifies the supporting and deterring factors to introducing PPMOF on a given project.

PRECAST BRICK PANELS

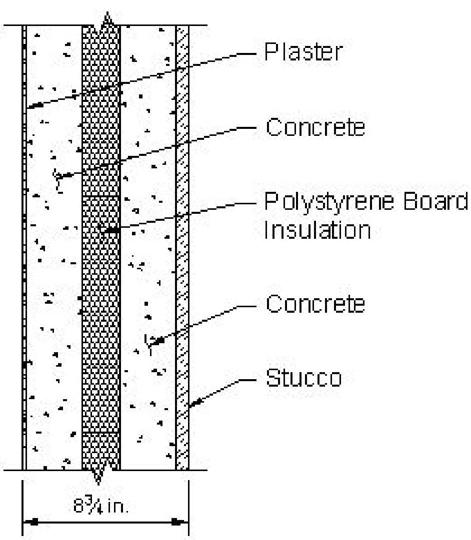
Rising material, fuel, and labor costs drive the market toward prefabrication. Precast façade panels allow for faster, more economical construction and can be constructed year round, as opposed to the temperature-sensitive concrete that is delayed in extreme weather conditions. Precast panels sometimes allow for a reduction in the structural system—smaller beams and columns— because panels are lightweight. The precast panel industry has come a long way from 'standard vanilla.' Panels can be highly customized with a multitude of exterior finishes, pre-installed windows, and pre-finished interiors.

Precast concrete brick panels are a new technology that the construction industry is embracing today. Some of their benefits include superior strength and durability, design flexibility, aesthetic diversity, minimal site impact, faster construction time, and reduced life cycle costs. There are four main types of precast panels: curtain walls, load-bearing wall units, shear walls, and formwork.

Many precast concrete panels consist of a reinforced concrete panel with brick facing. They are connected to the structure via clips or angles embedded in the concrete slab or welded to steel beams. The downside to this type of precast is that insulation and moisture protection is still required behind the panels. Installation of these elements can be difficult when trades are faced with hard-to-reach spaces.

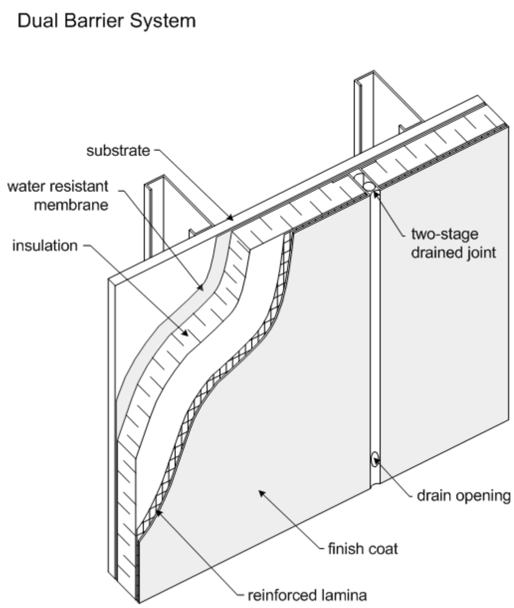


Precast Concrete Panel



Sandwich Panel

Sandwich panels are another option. This precast system consists of closed cell insulation between two concrete panels. They do not have much better thermal properties than traditional precast panels because the layer of insulation is so thin. Thermal performance of a wall system depends primarily on the thickness and density of insulation placed in the wall cavity. The thicker the insulation, the better the thermal properties. These panels are popular in construction because they come with pre-finished interiors. The downside to this is that the contractor must take extra care not to damage the drywall while placing the panel.



EIFS Dual System Barrier

Similar to sandwich panels is EIFS (Exterior Insulating Finishing System), a synthetic stucco panel system that relies primarily on its outermost layer to protect against moisture penetration. A typical panel is composed of polymer based synthetic stucco on top of expanded polystyrene insulation board on top of plywood sheathing. This very thin and lightweight panel attracts buyers to the product. For EIFS to be effective, all of the water must be stopped at the exterior surface, and this is hardly ever the case. The diagram shows a more sophisticated EIFS system that provides more safeguards against thermal and moisture penetration.

Prefabricated Whole Brick Panels

As has been discussed at the PACE conference, in classes, and in research, there is a lack of skilled labor in the construction industry today. Whether through subliminal messaging from the media or the influence of teachers and parents, young people no longer view construction work as a "good job." Physical labor is viewed as grunt work. People who are uninterested in attending college are turning to technical institutes to acquire the certification to manage construction work in a shorter time frame than a typical 4 year university. The industry is getting to a point where there are too many people managing work but not enough people actually performing the work. These two sides of construction are equally important, but there is certainly more emphasis on the management side. Industry is suffering greatly from the lack of skilled labor.

Prefabricated whole brick panels are one innovation present in very few places in the United States. Basically, these brick panels are hand laid at off-site location using clay bricks and mortar. They have every resemblance to stick built brick façade, except they require structural support to hang them on the building.

It was interesting to learn the logistics of how these panels operate. The panel is hung from a connector near the top. Since the lower portion is in tension, the panel behaves as a beam and supports its own weight. The panels are designed as reinforced masonry. Reinforcement is installed in both directions, and a typical panel is about 7 feet high by 3- feet long.

Similar to laid-in-place brick, brick panel walls are not insulated. Manufacturers recommend a full back-up system including a vapor seal. Completed brick panels are washed and damp proofed with a clear water-repellant coating.

I see great potential in this construction technique and so do some industry professionals. I spoke with an engineer at KPFF in Seattle, Washington, who has been designing these systems for several years. He says that he sees a future for prefabricated brick, but unfortunately, manufacturers are not catching on. Vet-O-Vitz is a company based in Ohio that fabricated these panels for a while, but, due to a lack of sufficient demand, they have gone out of business. So, there must be a joint effort between designers and suppliers to implement these panels. Construction managers need to suggest these products to inexperienced owners and get the word out about whole brick panels.

Whole brick panels have some benefits over precast concrete thin brick panels. Since these panels are built by hand in controlled environments, the quality of construction is much higher. Custom formwork does not drive up the cost of production, and the mason has much more freedom of design. Also, these whole brick panels look and feel like 'real' hand laid brick. It is the next best thing to site-constructed brick facades, and to some owners, authenticity is of utmost importance. Thermal and acoustical properties are not compromised; the whole brick panels are even more massive than hand-laid due to their structural reinforcing. Another major advantage to using any kind of prefabricated building skin is the elimination of scaffolding to construct the façade. This saves the owner a great deal of money and eliminates the insurance risks associated with masons working hundreds of feet in the air.

In a paper published in 1999, Fred Galassi of Barkshire Panels Systems states that their competition is not laid in place brick, but other skin systems like metal or precast. He explains that whole brick panels are usually less expensive than precast systems, but more expensive than hand-laid brick. I think prefabricated whole brick panels could be a viable construction option if there were an increase in manufacturers across the US and an influx of skilled factory workers to erect the panels.

The Future of Prefabrication

In a highly automated time, construction is one industry that makes little use of technological advances when it comes to the equipment used onsite. The methods used to construct a brick wall are essentially the same as they were 6,000 years ago. The managerial side sees improvements like savvy computer programs to assist with scheduling and coordinating tasks, but the field staff lives in a different world. Some subcontractors are living in a time where hand-drawn plans are the norm while general contracting firms are working form cutting edge building information models. So when will we see some advancement in the labor force?

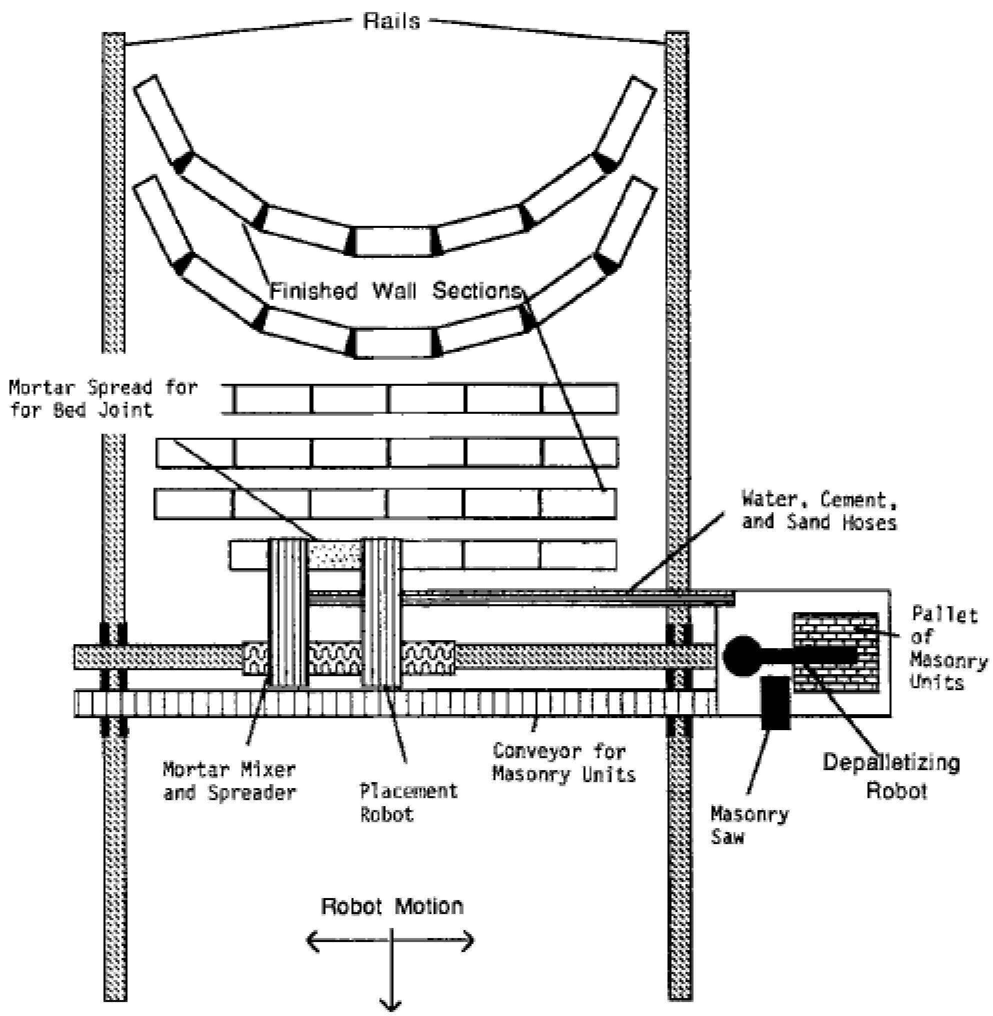
Another problem with field labor is the lack of skilled workers. I remember my summer internship from two years ago. We had a lot of people onsite, but only a select few actually knew what they were doing. It slowed down production so much and posed a dangerous situation because many of the workers were unaware of safe work practices. They operated on a 'do as you're told' basis. Otherwise they stood around waiting for orders. If everyone on a jobsite were a skilled worker, tasks would get done a lot quicker, safer, and with higher quality.

One area that is currently under investigation for the future of prefabricated brick technology is the use of robots to construct brick panels in a controlled environment. In a case study titled "Prototype Robotic Masonry System," the authors consider masonry to be a good candidate for robotization because it is tedious, unpleasant, physically demanding and critical to finishing projects on time. One automated system was explored by Anliker in 1988. He detailed a semi-automatic machine that can construct walls up to 8 feet long. The $80,000 system required the help of two men and could produce 30-35 square meters of wall sections per day. Later in 1989, scientist Lehtinen et al. determined that a masonry robot could be built for approximately $330,000 with an estimated payback period of 6 years. To date, no fully automated masonry system has been built and tested in the United States.

A research team at the University of Maryland is attempting to produce a prototype bricklayer that could be integrated into a flexible manufacturing system (FMS). An FMS is defined as an automated production system that is capable of producing a range of products with minimal manual intervention. The team has broken masonry construction into six main processes:

1. Preparation of mortar
2. Preparation of units
3. Delivery of mortar
4. Delivery of units
5. Spreading of mortar
6. Laying of unit

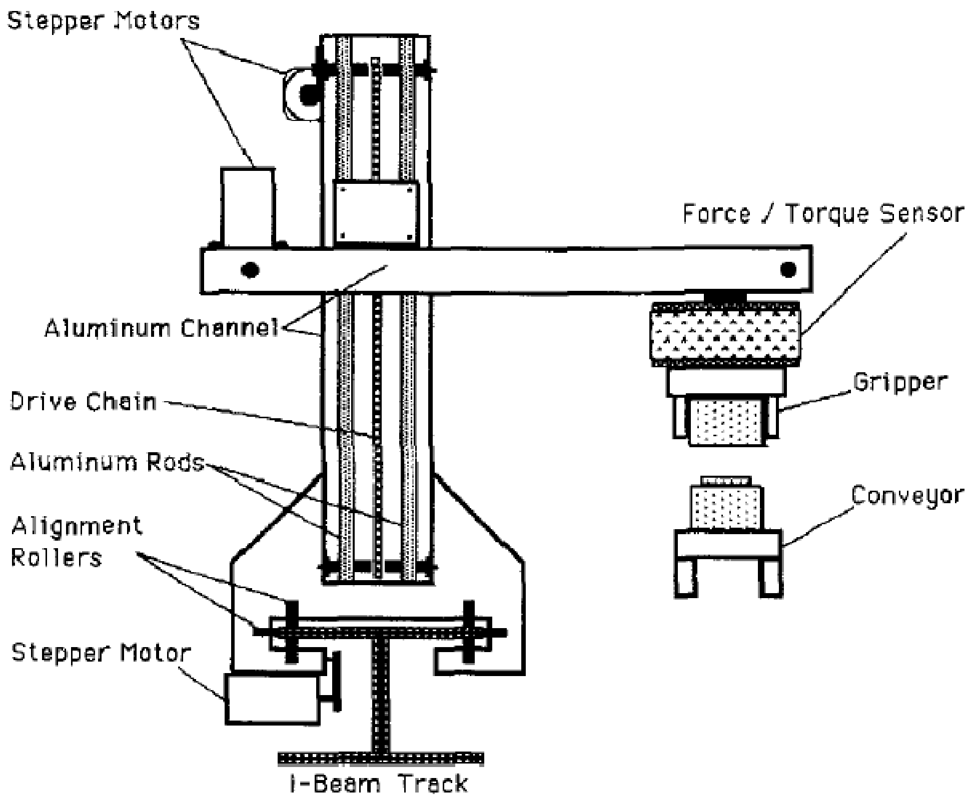
The figure below demonstrates a proposed system of a semi-fixed production unit. The basic framework is a gantry arrangement that moves back and forth on rails. The work center at the end of the frame cuts and places masonry units on a conveyor belt that transports them to the placement center in the middle of the figure. The placement cells contain the mortar mixer, spreader, and laying robot. The gantry can move in both horizontal and vertical planes so that it can reach all points of the wall for placement. It also has some rotational movement to account for inaccuracies. Water, sand, and cement are delivered to the mixer beside the robot through hoses. The mortar is mixed and spread on demand, eliminating problems with expired mortar mixes or clogged hoses.



General concept for robotic masonry system

Extensive testing revealed that the robot's placement was fairly accurate with a standard deviation of 0.055 inches. The Initial Rate of Absorption tests showed that the bricks had fewer pores which means less surface area for mechanical bonding of bricks. To remedy this, greater force must be applied when placing bricks. The mortar spreader produced uniform beds of mortar, although some clumping problems persisted in the spreader head. The bond strength results further proved that the bricks were not placed with enough force to properly adhere to the mortar. The placement method needs to be revised.

One aspect of the brick robot system that was not researched by the Maryland team but is critical to the success of the prototype is the interface between computer systems. The programmability of the machine will determine its effectiveness and conformance to standards.



Brick-Laying Workstation

The brick robot is an emerging technology that could revolutionize brick-laying and certainly address the issue of a dwindling work force. Although not such a popular research topic today, I can see how this unconventional technology could take flight in the future, especially if used to produce the whole brick panels mentioned in the previous section.

Conclusion

This depth study has identified some driving factors for prefabrication to be cost, schedule, and workforce issues. Some of the barriers to prefabrication were additional planning, transportation difficulties, design inflexibility, and more advanced procurement requirements. I think it is important to note that while software programs can crunch numbers faster than people, the decision to use prefabrication on a project is usually best made by a human. A computer cannot be taught common sense and basic instincts. I do think that the CII structure simplifies the thinking process and prioritizes the owner's requests.

In my quest for a panelized brick system I found the whole brick panels to be a unique product. I heard of one project that utilized a system similar to this, but it is obviously not a widespread

industry practice. I see this as such an innovation for the construction world. Quality and authenticity can coexist with low cost and schedule time. I almost selected these panels for my Analysis 1, but decided against the idea when I discovered the closest manufacturer of these panels is in Ohio.

The brick robot may seem a bit far-fetched, but I completely agree with the researchers that in a highly automated time, construction lags behind the technology curve. The brick-laying process is a tedious and physically taxing activity that often results in worker injury. If robots can accomplish the same task and eliminate that risk, I am all for it. Skilled masons would still be hired for complex masonry work, but the monotonous and repetitive sections could be handled by machines.