

# Tablet and Wearable Computers for Integrated Design and Construction<sup>1</sup>

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## Abstract

Integrated design and construction teams rely on rapid information exchange between the design office and the point of work on site during construction. But existing means of communication are not compatible with the rugged setting of the construction jobsite, where both paper documents and electronic equipment may be easily damaged or destroyed. Recent advances in rugged, affordable, portable computers promise to dramatically improve communication between construction personnel at the point of work on site and their off-site collaborators. Using a wireless-enabled tablet or wearable computer, a field worker can access the project information needed to complete a task without ever leaving the point of work. Pen-based tablet computers are becoming a popular alternative to keyboard-input notebook computers. Wearable computers are in use today by emergency medical personnel, firefighters and others requiring extreme mobility and instantaneous information access at their point of work. This paper presents the results of the University of Illinois at Urbana-Champaign study on this new breed of wireless-enabled portable computers for integrated design and construction. It discusses opportunities for saving time and money on integrated projects, and issues in implementing this innovative technology. Results indicate that tablet and wearable computers may significantly reduce rework, while productivity decreased slightly when tablet and wearable computers were used.

## Research Problem and Overview

Building design and construction is the world's largest industry. It is also one of its most inefficient. Consensus estimates suggest that as much as 30% of project costs are wasted through poor management of the design-construction process (Brown and Beaton 1990). This waste represents over \$10 billion in the US every year that could be directed toward improved design, better materials and related improvements to our built environment. Much of this waste has been attributed to the extreme separation of design and construction characterizing the building industry today (Peña-Mora and Li 2001). Under this paradigm of separation, an architect produces design documents and then hands them off to the contractor for production, frequently with little collaboration between the two parties. Increased integration of design and construction is now being called for as an effective means of reducing waste in the building industry. But a serious obstacle to integration still exists. Greater collaboration between disciplines requires more frequent communication, and poor communication is already blamed for much of the waste undermining the production of buildings today (Chaaya and Jaafari 2001, Pietroforte 1997). Unless current communication technologies and practices are improved dramatically, greater integration of design and construction could actually increase waste as it increases communication.

Communication problems in the building industry are most apparent in the breakdown of information exchange at the point of work on the construction jobsite (Hameri, Nihtila and Rehn 1999). Existing means of communication are not compatible with the rugged and isolated setting of the construction jobsite, where both paper documents and electronic equipment may be easily damaged or destroyed. The recent advent of affordable tablet and wearable computers, however, offers considerable promise in overcoming the problem of on-site communication. This study measured the impact of tablet and wearable computers on project communication at the task level of work on site. Case studies were used to define critical variables in design-construction communication, and laboratory experiments were conducted at the University of Illinois' Building Research Council facilities to measure the accuracy, timeliness, completeness and efficiency of information exchange enabled by wearable computers. The result is a comprehensive evaluation of tablet and wearable computers for integrated design and

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construction with the aim of improving task level communication and reducing waste in building design and construction.

### **Research Goals and Objectives**

The fundamental research hypothesis addressed in this study was this: The use of tablet and wearable computers improves communication between the fieldworkers at the point of work on site and off-site collaborators in building design and construction. The purpose of this study was to measure the accuracy, timeliness, completeness and efficiency of information exchange enabled by tablet and wearable computers relative to that enabled by other communication devices. This study was part of a larger research program at the University of Illinois at Urbana-Champaign to develop tools and practices for improving the built environment through integrated design and construction. The correlation between increased integration and improved building quality has been established (Fergusson 1993), and the importance of communication to integration has been defined by this study's principal investigator and others (Elvin 1998; Pocock, Liu and Kim 1997; Vanegas 1987).

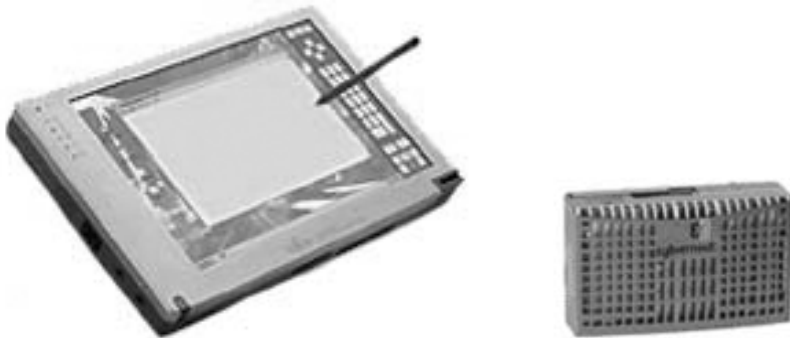
### **Background**

Twentieth Century building design and construction has been characterized by a very clear separation between the design and construction organizations involved in the project, and a very clear separation between the design and construction phases of the building process. But this organizational and sequential separation has come at a price, frequently resulting in construction schedule delays, cost overruns, increased litigation, and poor building quality (de la Garza et.al. 1994). When separation between design and production was found to cause similar problems in the manufacturing industry in the 1970's, the industry responded with the strategy of "concurrent engineering." Prior to the introduction of concurrent engineering, product designers typically completed their design work and then handed off plans and specifications to a production team responsible for manufacture, a method still employed in the building industry today. With the introduction of concurrent engineering, multidisciplinary teams of designers, engineers and production supervisors now perform design and production tasks concurrently, resulting in an improved fit between the design of the product and the means of its production. The introduction of concurrent engineering to the manufacturing industry has resulted in reduced production costs and schedules, and an increase in product quality (Evbomwan and Anumba 1996).

The success of concurrent engineering in the manufacturing industry has led many to call for its application to the building industry. Under a variety of names, including "integrated design and construction" (Elvin 1998), "concurrent construction" (Jaafari 1997), "concurrent life-cycle design and construction" (Anumba, Baron and Evbomwan 1997), and "the new production philosophy" (Koskela 1992), these theories call for increased collaboration and concurrency of design and construction to overcome the inefficiencies of 20<sup>th</sup> Century building production. But the application of concurrent engineering to the building industry has been hampered by one key difference between manufacturing and building. In manufacturing, the production environment is tightly controlled – assembly lines are enclosed in factories, and design and production personnel are likely to be collocated at the same plant. In building, however, the production environment is outdoors, far from the home offices of designer and constructor. The ruggedness and isolation of the outdoor setting can make communication extremely difficult. Whereas in a factory setting project information may be brought to the point of production with relative ease, on the construction jobsite both paper documents and conventional computers are unwieldy and susceptible to damage at the point of work.

This difference between manufacturing and construction is critical because increased information exchange between team members has been identified as both the principal reason for concurrent engineering's success and the greatest challenge to its implementation (Fergusson 1993). Yet communication becomes much more difficult when the point of production is a harsh outdoor environment far from the home offices of designer and constructor. Coordination and communication frequently break down because project information is not accessible at the point of work, as evidenced by the fact that contractors cite waiting for design information as the principal cause of delays in construction today (Kumaraswamy and Chan 1998).

The construction industry has yet to solve the problem of communication at the point of production on site, and many experts suggest that this is the principal cause of the management inefficiencies costing the US \$30 billion per year (Day 1996). Large-format paper documents are almost unusable at the point of work because of their volume, fragility, and, in concurrent design and construction, the likelihood that the project information they contain is out of date. Notebook computers are too fragile, and keyboard input is awkward in a construction setting. However, emerging innovations in personal computing hold considerable hope for improving communication at the point of work on site. Tablet computers, similar in size to a notebook computer, use a touch-sensitive screen for input using a pen-shaped stylus rather than a keyboard (Figure 1 left). Wearable computers, which consist of a processing unit and batteries worn on a belt accompanied by a variety of data input and display options (Figure 1 right), may potentially overcome many of the obstacles that have hindered on-site information exchange in the past. Using a wearable computer, a field worker can easily access the project information needed to complete a task without ever leaving the point of work, greatly improving process efficiency (Mann 1998). Wearable computers are in use today by emergency medical personnel, firefighters and others requiring extreme mobility, hands-free operation and instantaneous information access at their point of work.



**Figure 1. Tablet computer (left) and wearable computer (right).**

Experimental prototypes of wearable computers for construction have also been tested, much of the leading work being conducted at the University of Illinois at Urbana-Champaign (Liu 1995). The study described here differs from previous UIUC studies in two ways. Whereas those studies explored the potential of wearable computers for construction management, this study examines their role in integrating design and construction activities. And while those studies aimed to develop experimental prototypes, this one uses Commercial Off-The-Shelf (COTS) hardware that is now affordable to most design and construction firms. The use of wearable computers has been shown to reduce communication delays and increase worker productivity in other fields (Siegel et.al. 1995). Because of their ability to bring project information to the point of work on site, wearable computers may prove to be the “missing link” in information technology that finally allows the benefits of concurrent engineering to be realized in the building industry.

### **Importance of the Study**

If the benefits of integrated design and construction are to be realized in the construction industry, study is required to determine the effect of tablet and wearable computers on project communication and work tasks. Research to date on wearable computers for the building industry has focused on the invention of prototype units for construction management (Liu and Lustig 1995). These proof-of-concept explorations have been extremely significant in suggesting the viability of wearable computers for on-site information exchange, but to date no comprehensive study of their effect on the performance of design-construction communication and work tasks has been attempted. This is a crucial gap in existing research for two reasons.

First, the principles of integrated design and construction demand effective communication at the task level, at the point of work on site. A detailed investigation of the effects of tablet and wearable computers on the performance of integrated design-construction communication is essential in determining their value in the implementation of concurrent engineering. Currently, jobsite workers in construction spend only one third of their time actually engaged in productive work; the rest is waiting or unproductive work (rework) (Sweet 1994). Project-level re-engineering of the building process cannot, by itself, correct this deficiency when current communication technology prevents effective information access at the point of work. Waiting for design information is known to be the principal cause of delays in on-site construction work today, so the problem must be solved at the point of work. Only when this task-level bottleneck is resolved can the benefits of concurrent engineering be achieved at a larger scale.

The second reason for undertaking this investigation is that tablet and wearable computers are now available on the market for about the same cost as a typical high-end desktop computer that any design or construction firm can purchase. Proof-of-concept studies testing custom-built wearable computers have established their applicability to field task performance, and now research is needed on the use of off-the-shelf units for task-level information access. If the extreme wastefulness of the design-construction process is attributable mainly to poor communication, as many argue it is, the case for a portable yet powerful information exchange device at the point of work on site is compelling. The role of technology in economic growth through improved productivity is well established, and in an industry where billions of dollars are wasted every year due to poor communication, the potential for economic growth through increased efficiency is considerable.

## **Methods**

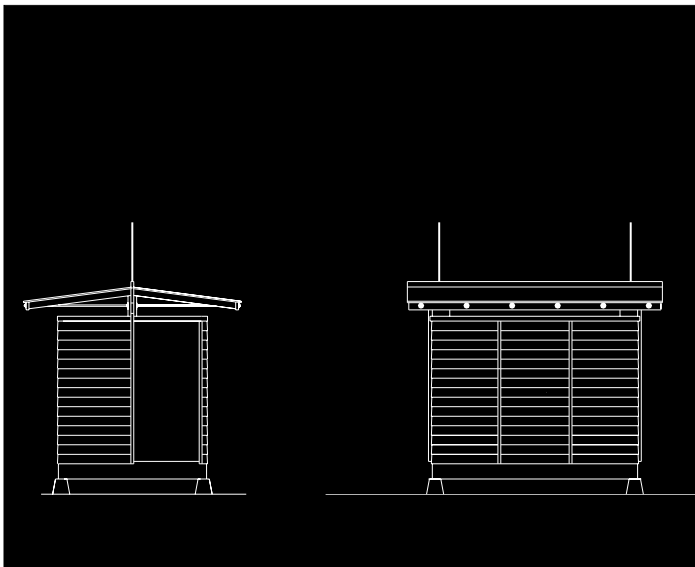
In this study, structured interviews, case study field observations, and controlled experiments were combined in order to measure the impact of wearable computers on project communication. Structured interviews were first used to gather data on project communication. These interviews were then complemented by direct field observation of on-site design and construction in progress on case study projects. The logical framework derived from interviews and on-site observations was used to structure the collection of data in the experimental phase that followed, in which the researchers designed and constructed three small structures at the Building Research Council laboratory on the UIUC campus (Figure 2). This experimental method of participant observation, in which the experimenters participate in the activities being studied, was necessitated by the difficulty of obtaining accurate data from field experiments on commercial construction jobsites, where personnel are mobile, in a dangerous setting, and under intense pressure to complete the task at hand. In contrast to field experiments, the laboratory experiments conducted in this study made it possible to control exogenous variables such as cost, schedule, safety, materials, site, weather and design, and focus on measuring indicators of improvement in project communication.

In each experiment a different type of communication device was employed while other variables in the project were held constant. The three communication technologies tested were 1) paper documents, 2) pen-based tablet computer, and 3) wearable computer with flat panel display. The first experiment, using paper documents only, served as the control group for the study, as paper documents are still the primary means of graphic information exchange on construction sites today. A review of academic and industry literature suggests that pen-based tablet computers may offer a viable alternative for on-site communication (Liu 2000), and their use was tested in the second experiment using a Fujitsu Stylistic 3500 tablet computer. The final experiment was conducted using a Xybernaut MA V wearable computer.



**Figure 2. Wearable computers allow construction personnel access to project information at the point of work on site; here the computer is tucked into the constructor's nail pouch.**

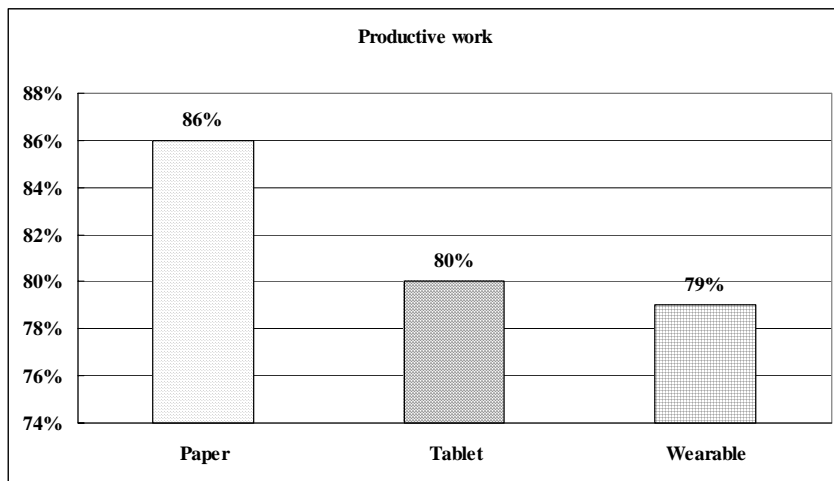
In each experiment, a research assistant acting as constructor was required to collaborate with a remote designer. A second research assistant, present in the laboratory but not engaged in construction, conducted ongoing protocol analysis to collect detailed data on information exchange and task performance. To determine the impact of wearable computers on design-construction integration, variables in communication, design-construction task iteration, and general task performance were measured. In each case, the constructor began the project with only 30% of the information required to complete the project (Figure 3). Teams completed the construction and collaborative design of one structure using a particular communication technology, and then completed a similar structure using a different communication technology. Design was varied with each structure to avoid the risk of maturation, (increased efficiency resulting from repetition of tasks in the course of the experiments.)



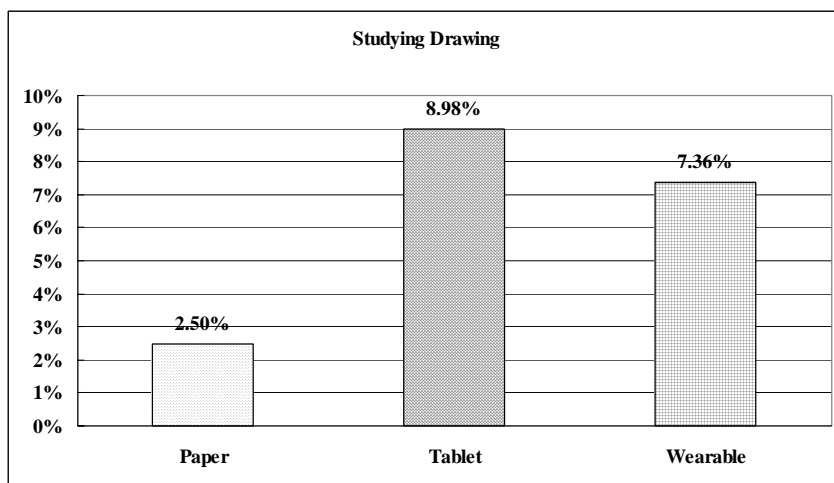
**Figure 3. An initial CAD drawing for one of the three structures as provided to the constructor, containing approximately 30% of the total information needed to complete construction.**

## Results

**Productivity** – Productivity was slightly lower in the projects using tablet and wearable computers than in the project using paper documents. Specifically, productive work accounted for 86% of the total project time when paper documents were used, 80% with a tablet computer, and 79% with a wearable computer (Table 1). The reduced productivity found in projects using tablet and wearable computers may be attributable to the greater time required to navigate CAD documents on site on a device with a relatively small screen. In the case of the paper document project, 2.5% of total project time was spent studying the project documents. In the case of tablet computers, 8.98% of project time, and for wearable computers, 7.37% of total project time (Table 2). These findings may reflect the difficulty of performing construction work while using a computer. However, the experiments did not measure the productivity impacts of managing a large volume of documents, as would be necessary on a large building project. Using a tablet or wearable computer it is possible to manage a large volume of project data, whereas an accumulation of paper documents at the point of work could begin to reduce productivity.



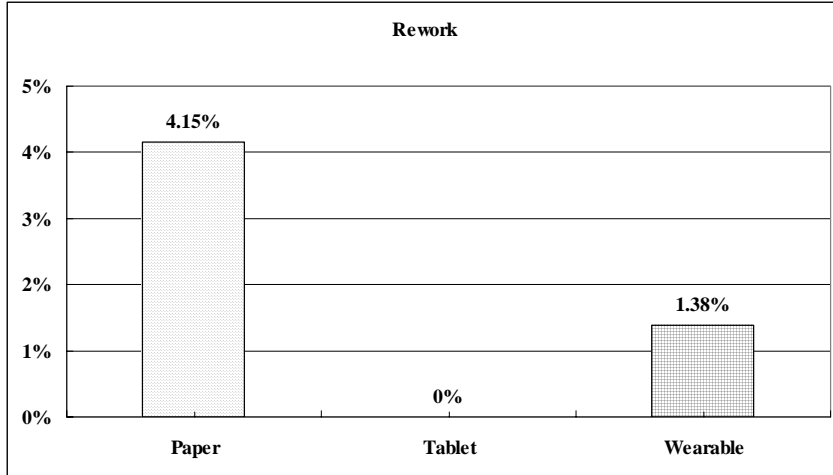
**Table 1. Productive work as a percentage of total project work**



**Table 2. Percentage of time spent studying and navigating project documents**

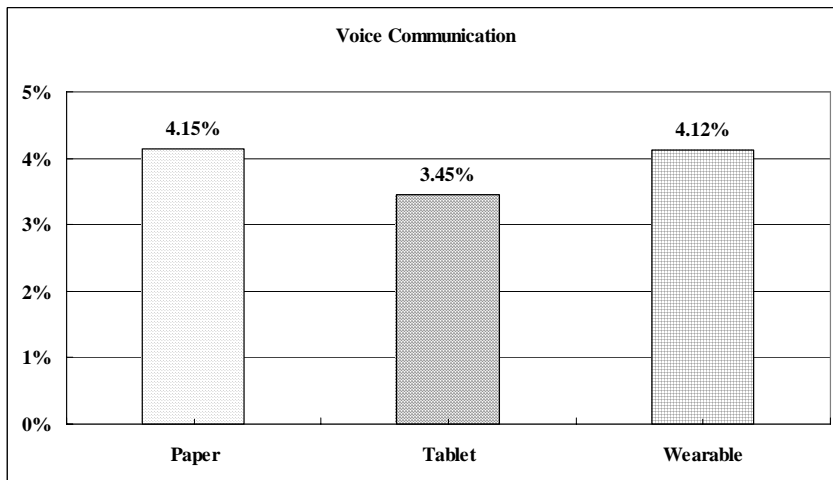
**Rework** –Rework required was significantly lower in the projects employing tablet and wearable computers than in the project employing paper documents. In the case of paper documents, 4.15% of total project time was spent engaged in rework; in the tablet computer case, 0%, and in the wearable case, 1.38% (Table 3). There are several possible causes for the reduction in rework when computers

are employed on site. Paper documents were faxed to the site as is typical in contemporary construction projects, and the quality of the documents received is extremely unreliable. Also, CAD documents may be enlarged on screen to any level of detail, making their details clearer to the person interpreting them than paper documents allow. The tablet computer's larger screen (10.75" diagonal) may have been a factor in its slight improvement in rework reduction over the wearable computer with its 8.5" screen.

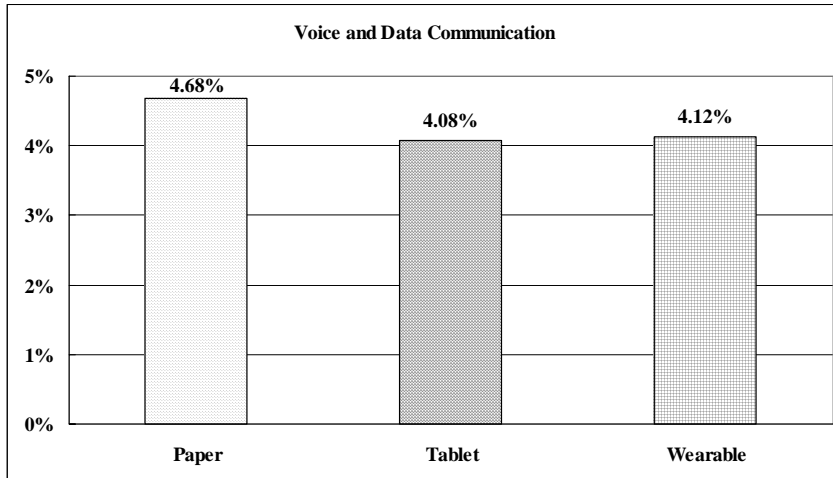


**Table 3. Rework as a percentage of total project time**

**Voice Communication** – No significant difference was found in the amount of voice communication required in the three projects. Voice communication accounted for 4.15% of total project time in the paper-based project, 3.54% in the tablet computer project, and 4.12% in the wearable computer project (Table 4). This indicates that computer-based data exchange between the designer's office and the point of work on site may not be a substitute for voice communication between designer and builder. When we look at voice and data communication combined, the combination accounts for 4.68% of total project time in the case of paper documents, 4.08% when using tablet computers, and 4.12% when using wearable computers; again, not a significant difference (Table 5). This result indicates that fetching faxes from a jobsite office roughly balanced with the time required to send and receive documents over the computer using a wireless Local Area Network. However, while the time required to fetch faxes would remain constant with more experience, the time required to exchange documents via the computer could decrease with improvements in data transfer speed and user experience.



**Table 4. Voice communication as a percentage of total project time**



**Table 5. Voice and data communication as a percentage of total project time**

### Conclusions

The results suggest that tablet and wearable computers can improve communication between the fieldworkers at the point of work on site and off-site collaborators in building design and construction. They also point to some areas of concern in the adoption of these new technologies. The most serious concern was the 8% decline in productivity observed when using tablet or wearable computers as opposed to paper documents. However, this decline is typical of the initial decline in productivity observed when a new technology is introduced to a workforce in any field. Further study is needed to determine the long-term productivity impacts of tablet and wearable computers once the user has become proficient in their use. The largest factor in the productivity decline was the increased time spent navigating and studying drawings when using the tablet or wearable computer. Time spent navigating and studying drawings when using the wearable computer was almost three times that spent navigating and studying paper documents, and even greater when using the tablet computer. The finding that productivity showed a similar decline when either a tablet computer or wearable was used suggests that the pen-based interface used by both devices may slow document navigation and study. Currently, users are accustomed to the more traditional keyboard and mouse interface. Productivity may improve if the recent promotion of pen-based tablet computers by Microsoft and several hardware manufacturers is successful and users become more familiar with this interface.

The time required to navigate and study drawings was undoubtedly influenced by the small scale of the experimental projects. Eighteen 8.5"x11" paper documents were needed to complete the paper-based project – a fairly manageable quantity. However, on more complex projects requiring hundreds or thousands of documents, the results could differ; a tablet or wearable computer could, in principle, provide access to a large number of drawings which would be unmanageable in paper form at the point of work. Further study is recommended measuring the productivity impacts of electronic versus paper document management at the point of work on larger project.

The tablet and wearable computer achieved similar results in most of our tests. Productivity, voice and data communication, and time spent studying and navigating project documents were all similar when using either the tablet or wearable computer. However, the small scale of the project and its secure laboratory environment allowed the constructor to set the tablet computer down while working. On a larger project damage or theft could be a greater concern, and the wearable computer, which can be stowed in a workbelt, could lead to improved productivity.

Using a wearable computer rather than paper documents for information exchange in building construction reduced rework by 66%. If this result may be applied to the construction industry as a whole, where rework accounts for 12% of total construction costs (de la Garza et. Al. 1994), the use of wearable computers could reduce total construction costs by 8%. The reduction in rework may be due to the wearable computer's ability to bring up-to-the-minute electronic project documents directly to the point of work on site. CAD drawings are more accurate than faxed paper documents, and may be enlarged to any level of detail. Furthermore, the constructor need not leave the point of work to exchange data, whereas faxed documents require the constructor to leave the point of work in order to pick up the fax at a jobsite office.

Using a tablet or wearable computer did not significantly reduce the amount of time spent on communication; Project time devoted to voice and data communication remained relatively unchanged whether using paper, a tablet computer or a wearable computer. But the reduction in rework suggests that, while the tablet and wearable computers did not reduce the quantity of communication, they may have improved its quality. We therefore consider the initial research hypothesis that tablet and wearable computers can improve communication between the fieldworkers at the point of work on site and off-site collaborators in building design and construction verified. If tablet and wearable computers do improve project communication, this may lead to a more efficient design-construction process and to savings that may be dedicated to improving the quality of our built environment.



**Figure 4. One of the three completed structures**

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