Innovation in the AEC Industry through Wireless Sensor Networks

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ABSTRACT

This thesis investigates the impact of Wireless Sensor Networks (WSN) on the Architecture, Engineering and Construction (AEC) industry. A review of the technological aspects of WSN is conducted along with an analysis of the AEC industry. Evidence is presented that the biggest impact will be on structural health monitoring applications. It is noted that there will be significant business opportunities for this technology to improve the AEC industry. Detailed examples of its impact in the areas of design, construction quality control and maintenance are presented. The thesis concludes that the technology will be a sustaining force rather than disruptive force on the industry.

Thesis Supervisor: John R. Williams
Title: Associate Professor of Civil and Environmental Engineering
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# TABLE OF CONTENTS

LIST OF FIGURES............................................................................................................................................. 6

1. INTRODUCTION............................................................................................................................................... 7
   Motivation....................................................................................................................................................... 7
   Objectives.................................................................................................................................................... 8
   Roadmap of the Thesis................................................................................................................................. 9

2. OVERVIEW OF WIRELESS SENSOR NETWORKS......................................................................................... 10
   Introduction.................................................................................................................................................. 10
   Sensor Node technology............................................................................................................................... 11
   WSN challenges.......................................................................................................................................... 13
   WSN applications......................................................................................................................................... 14
   Conclusion.................................................................................................................................................. 15

3. WIRELESS SENSOR NETWORKS IN CIVIL ENGINEERING ....................................................................... 17
   Introduction................................................................................................................................................ 17
   WSN applications in Civil Engineering...................................................................................................... 17
   State-of-the-art in structural health monitoring........................................................................................ 19
   WSN for structural health monitoring......................................................................................................... 21
   Infrastructure Monitoring Projects............................................................................................................ 25
   The MIT Flagpole Project............................................................................................................................ 25
   A shake table test.......................................................................................................................................... 27
   The London Underground............................................................................................................................ 27
   The Alamosa Canyon Bridge....................................................................................................................... 29
   Technological challenges.............................................................................................................................. 30
   Conclusion................................................................................................................................................ 31

4. THE AEC INDUSTRY AND THE INNOVATION OF WSN ........................................................................... 33
   Introduction............................................................................................................................................... 33
   The AEC industry......................................................................................................................................... 33
   Characteristics............................................................................................................................................ 33
   Competition............................................................................................................................................... 35
LIST OF FIGURES

Figure 1: The traditional LEGO bricks ............................................................... 8
Figure 2: The 'new' LEGO smart brick ............................................................. 8
Figure 3: Generic sensor network .................................................................... 10
Figure 4: Wireless sensor node ........................................................................ 12
Figure 5: The MIT DuPont courtyard flagpole ............................................. 26
Figure 6: Graphical schema of the London Underground project ................... 28
Figure 7: Testing the Alamosa Bridge with a Modal Hammer ....................... 30
Figure 8: The 10 drivers of NIT ..................................................................... 38
Figure 9: WSN for Concrete Piles ................................................................. 60
Figure 10: A vision for the future: The smart brick .................................... 66
1. INTRODUCTION

Motivation

I came to the Massachusetts Institute of Technology (MIT) to learn about technological innovation and entrepreneurship. More precisely, I wanted to know more about how to leverage Information Technology (IT) in the Architecture, Engineering and Construction (AEC) Industry. IT can introduce great efficiencies and productivity gains in construction.

During my first weeks as a Master Student, two events lighted the spark that lead to this Thesis:

On one hand, I discovered Wireless Sensor Networks (WSN) through Prof. John R. Williams, when he proposed a topic for a Master of Engineering Project. WSN's are a new and promising technology. They exist thanks to recent advances in telecommunications, computing and sensing. A WSN consists of a network made of several small electronic devices (or nodes) that communicate wirelessly, often in a peer-to-peer fashion. Basically, WSN allow a spatio-temporal understanding of an environment. They can be used to monitor space, to monitor objects, and finally to monitor the interactions between those objects and their surrounding environment.

On the other hand, in one of my classes at the MIT Media Lab, Professor, Mitchel J. Resnick, talked about his LEGO smart bricks. Lego provides us with a compelling analogy of the transformation that WSN could bring to construction. Construction is one of the oldest industries and so it’s considered to be ‘traditional’. Likewise LEGO, a Danish company founded in 1932 and manufacturer of “small, uninteresting, plastic bricks that kids could play with” (Sammut, 2002. See Figure 1), was considered an old-fashioned product manufacturer until recently. But in 1998, Lego started to commercialize a revolutionary robotics kit based on Resnick’s idea of a programmable “smart”
Lego brick (see Figure 2). The launch has been a commercial success since then.

This is a fascinating story. It is the tale of how innovation can even take place in the most unexpected places. If this has been done to a small, plastic brick, what could be done to construction products?

**Objectives**

This Thesis ties together the construction industry (the ‘bricks’) and information technologies (the ‘bits’). It also analyzes how the concept of the LEGO “smart-brick” can be extrapolated to infrastructure. Can we anticipate the future of WSN in the AEC industry? Finally, it analyzes the business opportunities that this technology may bring.
Roadmap of the Thesis

This Thesis is organized as follows. Chapter 2 and Chapter 3 cover the technological aspects of WSN, providing a first 'building block': the 'Technology'. Chapter 2 provides a holistic overview of WSN, describes their characteristics, the technical challenges that still exist, and the main areas where this technology may be applied. Chapter 3 focuses on the characteristics of WSN for structural health monitoring, which is the area in Civil Engineering that holds more promise. It describes the state-of-the-art of the technology in this field, compares it to 'traditional' wired structural health monitoring systems, and again, describes the technical challenges that need to be solved. Also in this Chapter there are brief summaries of the first 'real world' WSN deployments and the lessons learned in those deployments.

Chapter 4 is the second 'building block' of the Thesis: the 'Context'. It has three parts. The first part describes the Architecture, Engineering and Construction Industry, focusing on its characteristics and digital intensity. The second part describes the nature of technological innovation, and concentrates on the concept of disruptive innovations. Finally, the last part of the Chapter analyzes how innovation takes place in the AEC industry and discusses the type of innovations WSN may bring to the industry.

Chapter 5 is built upon the previous two 'building blocks'. On one hand, a 'Technology'. On the other hand, a 'Context' in which the Technology may be applied. This Chapter proposes several applications in which WSN may be a source of innovation in the AEC industry. There's a special emphasis on structural health monitoring and an Executive Summary of a fictitious start-up is included.

Finally, Chapter 6 summarizes and concludes this Thesis. It also includes an afterword that introduces both an element of debate – the role of Civil Engineering in sensing - and a vision to be explored in further work.
Introduction

Wireless Sensor Networking (WSN) has been recently labeled as one of the most important technologies for the 21st century by prestigious publications like the Business Week or MIT Technology Review (Chong & Kumar, 2003). A WSN is a network made of sensor nodes that use wireless protocols as a means of communication. Each sensor node has one or various sensors and is deployed very close or inside a phenomenon (e.g., an example of a phenomenon could be change in temperature in a room). It monitors events, process and communicates the information gathered to other nodes in the network. Figure 3 shows a schematic representation of a WSN, where each node has multiple wireless links with other nodes and eventually to a base station that serves as a gateway for the network, bridging it with other networks like the Internet. Information moves node by node from the point of generation to the point of use.

Since each sensor node is wireless and usually has to operate for long periods of time, it has inherently strict energy resource constraints. This limitation in energy resources forces each sensor node to have very low power
consumption. To guarantee low power needs, sensor nodes have then a limited processing speed, storage capacity, and communication bandwidth.

However, to offset these limitations, a WSN leverages its resources in the aggregate (the sum of all the nodes in the network). Consequently, the deployment of nodes has to be highly dense and has to have a high degree of interaction between them (Culler et al., 2004). Moreover, the network has to be able to self-organize and self-heal when variations of connectivity occur or individual sensors nodes fail. Because of all these attributes, the communication protocols of the network are very complex.

Additionally, as Akyildiz et al. (2002) point out, there’s an extra constraint: the cost of deploying and maintaining a WSN must be low. In first place, a single node has to be very cheap. Since a WSN is composed of tens or hundreds of sensor nodes, the overall cost of the network must be cheaper than deploying traditional sensors. Ideally, the cost of a sensor node should be less than US $1. In second place, since WSN are expected to work unattended for a life-span of several years, they should also have a low cost of maintenance and operation.

As we can see, WSN are the result of merging technologies from three different areas: sensing, communications, and computing, combining a range of hardware, software, and algorithms. Recent advances in these three different areas - MEMS-based sensing technology, more reliable wireless communication, and low-cost manufacturing (Chong & Kumar, 2003) – had made possible the concept of WSN as we have previously briefly described. Next, in the following section we’ll take a closer look at the intricacies of these technologies.

**Sensor Node technology**

A sensors’ node is composed of four basic elements: a sensing unit, a processing unit, a transceiver unit and a power unit. The sensing unit includes the sensors (the eyes and ears of the node) and an analog-to-digital converter (ADC) that transforms the sensor’s analog signal to a digital stream for the processing unit. This processing unit, which is made up of a microprocessor
and a small storage unit or memory, manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks. The transceiver unit is usually a radio-frequency (RF) radio that connects a node to its neighbors. Lastly, the power unit is either a small battery or a power scavenging unit such as a solar cell.

Figure 4 is a schematic representation of a WSN node used in the project Great Duck Island Habitat Monitoring. We can distinguish a light sensing unit on top and a radiant light, humidity and pressure at the bottom; the battery unit - which is the biggest component; and also the processing and transceiver unit, both integrated in what is called Mica2Dot board, an off-the-shelf commercial product from Crossbow.

Figure 4: Wireless sensor node. (IEEE Computer Society. Computer Magazine, August 2004).

The networking capability of WSN’s is built up in several layers: the physical layer; the data link layer; the network layer; the transport layer; and the application layer. According to Akyildiz et al. (2002) and Culler et al. (2004), the physical layer controls the radio (Culler, 2004), manages frequency selection, carrier frequency generation, signal detection, and data encryption (Akyildiz et

1 At present, the technology with the most promise is the spread spectrum products commercially available, operating in the Industrial, Scientific and Medical Band (ISM) at 902-928 MHz.
The data link layer is responsible for the multiplexing of data streams, data frames detection, medium access and error control. It ensures reliable point-to-multipoint connections in a communication network (Akyildiz et al., 2002). In other words, it listens on the channel and transmits when the channel is clear (Culler, 2004). Finally, the network layer takes care of routing the data supplied by the transport layer. The transport layer helps to maintain the flow of data if the sensors network application requires it (e.g. when the system is to be accessed through the Internet or other external networks). Additionally, depending on the sensing tasks, different types of application software can be built and used on the application layer (Akyildiz et al., 2002).

**WSN challenges**

However, WSN potential cannot be currently fulfilled because some technical challenges still arise. The most important are:

- Conservation of power and bandwidth: Several approaches are being undertaken to overcome these constraints. The ultimate goal is to limit communication, which is the most energy-intensive operation—the other power consuming activities are sensing and data processing. To accomplish this, WSN can process data locally and only communicate information to the network when there is an interesting event; Aggregation of information within the network to reduce communication is another option; compression and scheduling can also be applied; finally, specific responsibilities can be assigned to certain nodes, such as retransmission or aggregation (Culler et al., 2004).

- Improvements in network technology and embedded software. Improvements are needed in the following areas (Chong & Kumar, 2003):
o Ad-hoc network discovery - Each node needs to know the identity and location of its neighbors. Relative positioning algorithms have to be provided;

o Network control and routing algorithms: to assure connectivity and network survival in dynamic, autonomous networks

o Collaborative signal and information processing: the degree of information sharing between nodes and how nodes fuse (process) other node’s information with their local information

o Tasking and querying: need of a simple interface to efficiently task and query the network

• Improvements in security and privacy: Like the Internet before, WSN are likely to face important security and privacy issues. The first one is the ability to be protected against intrusion and spoofing. Secondly, and perhaps more important, are the privacy issues that will arise when the data gathered by WSN will be made available. Who will control the data? For what purposes? (Culler et al., 2004).

**WSN applications**

We can finally turn our attention to the most interesting area of WSN: applications. There is a broad range of fields where WSN technologies can be applied. From a holistic point of view, WSN are intended to be deployed throughout a physical space, sense a physical phenomenon or event, and process and communicate this information to other nodes in the network. Therefore, as Culler et al. (2004) argue they allow a spatio-temporal understanding of an environment.

WSN applications can be grouped as follows (Culler et al., 2004):

• To monitor space: environmental and habitat monitoring, precision agriculture, micro climate study, indoor climate control, surveillance;
To monitor things: structural monitoring, condition-based equipment maintenance, medical diagnostics, and urban terrain mapping;

To monitor interactions of objects with each other and the surrounding space: wildlife habitats, disaster management, emergency response, asset tracking, health care, and manufacturing process flow.

Chong and Kumar (Chong & Kumar, 2003, p.1247) use an industry-based classification for WSN applications:

- Military sensing
- Physical security
- Air traffic control
- Traffic surveillance
- Video surveillance
- Industrial and manufacturing automation
- Distributed robotics
- Environment monitoring
- Building and structures monitoring

However, all these proposed applications remain mainly unexplored, as Akyildiz et al. pointed out in 2002. Things have certainly improved a little since then, but technology is still not yet ready to deliver results. There are still some very important technical difficulties to be solved.

**Conclusion**

This Chapter is a brief overview of the technology that composes WSN. If this technology succeeds in delivering high flexibility, high sensing fidelity, and low cost of deployment and maintenance (Akyildiz et al., 2002) they will have a place in almost every industry. WSN will then become an integral part of our lives, and we will be surrounded by thousands and millions of sensing devices.
However, as we have also mentioned in the Chapter, we are a few years ahead of this scenario. Some technical and systems challenges (data processing, communication, sensor management, etc.) need to be solved first.

Finally, it has to be mentioned that there's also a "gap between the hardware’s raw potential and its applications" (Culler et al., 2004) that has yet to be bridged. Although we have listed some of the most cited WSN applications, the question of what to do with the vast amounts of data is unanswered. Likewise, how can we couple this data with the Internet, network of networks? This is a challenging task.
3. WIRELESS SENSOR NETWORKS IN CIVIL ENGINEERING

Introduction

We have just learnt in the previous Chapter that WSN can monitor a physical environment, objects in that environment, and the interactions between objects and their environment (Martinez, Hart & Ong, 2004). This sentence accurately describes the WSN main uses in civil and environmental engineering: environmental monitoring and structural (or infrastructure) health monitoring.

We will focus in this chapter on the later\(^2\): structural health monitoring. We'll answer the basic questions: Why are WSN useful for? What parameters need to be monitored? What are the features a WSN for civil engineering applications must possess? We'll then take a look at the current state-of-the-art of the technology in structural health monitoring. Finally, we'll bring our attention to some of the first real-world deployments, including some projects undertaken at the Civil and Environmental Engineering (CEE) Department at MIT.

WSN applications in Civil Engineering

Civil Engineering is often synonymous of Infrastructure, the installations and other physical assets needed for the functioning of a society. This broad term refers to buildings, bridges, roads, traffic structures, sewer systems, water distributions systems, tunnels, ports, etc, which have the following characteristics: (i) large scale, both in number of components and size; (ii) long

\(^2\) Environmental monitoring applications are described in the MEng Project Report *Wireless Sensor Networks for Environmental Monitoring in the Boston Botanical Garden* by J. Ber and P. Hari. This project has served as the foundation work that has lead to this Thesis.
life; (iii) inaccessibility, either due to remote locations or the difficulties of dismantling a civil system apart in order to enact repairs; and (iv) uniqueness of every infrastructure (Radford, 2003).

Having said this, why would we want to monitor our infrastructure? There are two main purposes, public safety and cost reduction, either during construction or during operation. A WSN may help us to detect and locate damage in a structure, which is fundamental to address these both needs. Besides, sensors will also provide feedback to structural designers. As Green points out:

"If full time-history information were available at critical points in every structure, the mode and source of failure could be pinpointed and used as lessons in subsequent designs. This is where inexpensive and durable monitoring devices could make a deep impact in the health and longevity of not only structures, but of people as well" (Greene, 2001. p.13)

It’s obvious that failure of an infrastructure can cause considerable damage. Therefore, we have to find the means to obtain the certainty that our infrastructure is secure. The first way to guarantee this is through an appropriate design. The second way relies on regular monitoring and adequate maintenance (Radford, 2003). With an aging infrastructure in our societies and lack of appropriate funding to replace it, the later is becoming more and more important. Besides, the growing trend of life-cycle design is putting more emphasis on optimizing every dollar spent in maintenance and repair. It’s the search for improved system efficiency and lower costs (Radford, 2003).

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3 As an example, see Chapter 4 for a summary of the critical situation of some of the bridges in the United States.
State-of-the-art in structural health monitoring

Infrastructure (structural) monitoring refers to the collection and analysis of structural response to ambient or forced excitation (Xu et al., 2004). It can also be defined as determining, by measured parameters, the location and severity of damage as it happens (Chang, Flatau & Liu, 2003). The state-of-the-art of structural health monitoring can address effectively most of the concerns mentioned above. Safety and service condition in our buildings, bridges, etc. can be guaranteed. This is in fact a well-established area of research that has been around for many years. However, as we will see in this Section, existing procedures are expensive and cumbersome. They fail in providing a cost effective solution.

Currently, it can only be determined whether or not damage is present in the entire structure. The methods that provide this information are referred to as “global health monitoring”. Next, there are Non-Destructive Evaluation (NDE) methods to find the damage. These are referred as “local health monitoring” methods. NDE is time consuming and expensive, and access to the structure is not always possible or is very difficult (Chang et al., 2003)

Global health monitoring has been traditionally the tool used to determine the safety of structures like bridges. It consists of visual inspection and tap tests. Visual inspections are used to inspect for outward signs of distress, but are labor-intensive and dependent upon the inspector’s criteria. Tap pests consists on listening to audible variations in response to tapping the bridge surface to determine if voids or de-bonding exist. However, they are limited to finding voids near the surface of concrete, de-bonding of wraps, and in some cases significant cracks. Besides, NDE tests consist of acoustic emission, ultrasonic testing, and probable damage locations (Lynch, 2004)

Typically, structures safety and reliability ratings rely only on global health monitoring methods, which are inaccurate. This results in the retrofitting or replacement of many structures that, in some cases, need not be retrofitted or replaced. Worse is the possibility that some structures needing engineering renewal or replacement are not identified (Chang et al., 2003).
For critical infrastructure like singular long-span bridges, permanent monitoring systems can also be employed to continuously monitor the response of civil structures to external loads (Lynch, 2004). These systems made use of analysis procedures based either on modal or on physical (strain or corrosion) engineering parameters. The most common is a modal analysis of the recorded acceleration time histories. The results are the modal frequencies, mode shapes, and modal damping. This information can be used as input to a variety of engineering analysis procedures from finite element models to fatigue mechanisms to constitutive models (Straser, Kiremidjian & Meng, 2001). When damage occurs, the parameters of the structure model change. Engineers interpret these changes to assess the damage and its possible location.

To build these structural models, engineers rely on large data sets of structural response. Currently, these data sets are collected by expensive wired (or one hop wireless) and powered data acquisition systems. These systems typically consist of a single device that supports a fixed number of channels. Each channel is connected to one sensor located somewhere on the structure. The role of the centralized data server is to aggregate, store and process measurement data. The sensors simply take measurements and transmit them to the data server. A simpler, and cheaper, variant of a data acquisition system is a data logger - it lacks some of the analysis capabilities of a data acquisition system, and merely provides storage and high-bandwidth transmission capabilities for the collected data.

Data acquisition systems collect structural response either to ambient vibrations, or forced vibrations. Ambient vibrations are caused by earthquakes, traffic, or wind. Forced vibrations are caused by the engineers testing the structure. They deliver them by the means of large shakers, forcing the structure to vibrate at different frequencies (Xu et al., 2004).

The complete process of monitoring structural properties of a large civil structure consists of (Straser et al., 2001)

- Sense mechanical vibrations at several locations in the structure
- Convert these sensed vibrations into representative digital signals
• Transmit these signals wirelessly from the several locations to a central location
• Store and process this data to provide information useful in determining the structural condition of the civil structure

However, there is still a problem: the structural model is not known for most structures. Models are usually based on best guesses of what may be in the as-built structure. Another problem is that the condition of aging structural members is not known (Chang et al., 2003).

Besides, the hub-spoke architectures of data acquisition systems have poor scalability properties with systems comprised of hundreds of sensors, and are becoming increasingly expensive on a per channel basis. The computational demands of many of the damage detection algorithms that have been developed for structural health monitoring can be high. As the number of sensing nodes of the monitoring system increases, the centralized data server suffers an overflow of measurements and becomes overburdened in processing the data (Lynch, 2002).

**WSN for structural health monitoring**

Fortunately, WSN promise to overcome data acquisition systems limitations. They are a natural candidate for structural health monitoring systems because such systems require as many measurement points as possible to analyze both the global response and the local response of the civil structure. Based on the WSN general description in the previous chapter, it is easy to understand that WSN enable cost-effective dense in-situ sensing and simplify deployment of instrumentation (Xu et al., 2004). With WSN, it will be easier to integrate the operation phase of the infrastructure life cycle. Maintenance and rehabilitation will become more effective and efficient (Radford, 2003).

As we have seen, every structure has typical modes of vibration, acoustic emissions, and response to stimuli. Variations in these behaviors indicate wear,
fatigue, or other mechanical changes (Culler et al., 2004). WSN systems must then be able to detect vibrations and deviations from natural frequencies.

Typically, a WSN for structural monitoring will consist of:

- **Hardware:** Each sensor node has:
  - An accelerometer “mechanically coupled to the civil structure and producing an analog electrical signal representative of mechanical vibrations in a localized area of the civil structure” (Straser et al., 2001. p.2).
  - “A data acquisition circuit electrically coupled” to the accelerometer “and producing from the analog electrical signal a digital signal data stream representative of the mechanical vibrations” (Straser et al., 2001. p.2).
- A battery to supply power to the data acquisition circuit and radio
- Software solutions to process and store the data obtained from the WSN
- Data interpretation and visualization tools.

According to Chou (2004), the hardware has to have at least the following characteristics:

- 200 samples / sec
- Analog to Digital Converter (ADC) resolution: 10-12 bit
- 100m range minimum
- 5-100 nodes potentially
- Durable: last for weeks or months at a time and either low powered or high powered with renewable energy source (solar, vibration, wind)
- Cheap: $5-10 / node
- “smart”: self-calibration and self-diagnosis

Lynch (2004) argues that the following parameters are needed:
• ADC16-bits or higher
• Node-to-node communication ranges of over 150 m
• Capable of sampling rates as high as 100 kHz (structural response data is generated at higher data rates than most sensing applications; structures are typically sampled upwards of 100 Hz)

Xu et al. (2004) also agree with Lynch that the sampling resolution has to be at least 16 bits, and the sampling rate has to be greater than 100 Hz. Thus, an accelerometer would generate about 100 2-byte samples a second. And a sensor node attached to an accelerometer measuring accelerations along three axes would generate 600 bytes a second. He additional requires that accelerometers need to have a dynamic range of 1-2 g’s, sensitivity in the μg range and low noise characteristics.

Finally, according to Straser et al. (2001), the requirements for a WSN have to be:
• 16 bits
• At least 4 sensors per sensor unit
• At least 14.4 Kbps (wireless communication)
• 10 < # sensor units/structure < 100
• Form factor: less than 20 cubic inches
• Data acquisition rate: at least 200 Hz
• Distance between units at least 100 feet
• Data logging memory at least 8MB
• Sensor Unit Synchronization within 0.1 milliseconds
• Accelerometer dynamic range: less than 0.001 g to a few g’s
• Near real-time performance: within 30 minutes

As we can see, sampling rates are very high. This requires energy and memory to buffer the data. Unfortunately, as we know, WSN are characterized by having limited resources. So in order to reduce the amount of energy and memory necessary, WSN for structural health monitoring should perform some processing before transmitting the data. Rather than transmitting large amounts
of raw data, sensors nodes should do some signal analysis, and communicate only when anomalies are detected.

Besides, structural monitoring applications require loss intolerant data transmission and time synchronization of readings from different sensors (Xu et al., 2004). This is because in the analysis of structural response a spatio-temporal analysis is required. So WSN have to share a common, highly accurate time frame across nodes (Culler et al. 2004). Also important is instrumentation positioning. Sensors have to be placed properly, either in sections of maximum stress or maximum displacement.

The main parameter to be monitored is acceleration\(^4\) (to detect deviation of natural frequencies, as we have just said). Additional sensing parameters that can be monitored are:

- Strain
- Temperature
- Pressure
- wind speed
- GPS data

Finally, taking into account the civil infrastructure characteristics, a WSN monitoring system should also be:

- Low cost in order to make the technology feasible due to the large number of sensors needed (infrastructure large scale)
- Flexible to adapt to a variety of situations (uniqueness of every infrastructure)
- Long life. Similar longevity than the system being monitored is unfeasible with the current state-of-the-art. The WSN lifespan will be

\(^4\) The most commonly used sensor for monitoring vibrations in civil structures is the accelerometer. An accelerometer is a transducer that converts the local acceleration into a proportional electrical signal (an analog signal that is usually sampled and digitized). The most common sensor designs are based on piezo-electric, piezo-resistive, force-balance, or capacitive principles.
determined based on factors like the intended purpose or application and the replacement cost of the system. Moreover, there's no need to monitor the infrastructure 24 hours a day, 365 days a year, except when there's an element of concern. A WSN monitoring system could only check structural health at pre-determined long intervals of time and be able to turn to a more frequent or continuous monitoring when wished. (Hudson, 2002

- Reliability and low cost maintenance

Infrastructure Monitoring Projects

Several WSN infrastructure monitoring projects have been identified, both in MIT and other leading institutions worldwide. Next, in chronological order, there is a summary of the most revealing projects, as well as the lessons learned from them.

The MIT Flagpole Project\textsuperscript{5}

The Flagpole Project was a 2.001-2.002 Project at the MIT Civil and Environmental Engineering Department financed by the Microsoft i-Labs initiative. The project consisted on the design and implementation of an scaleable, real-time virtual laboratory to monitor physical infrastructure. A 102 ft high flagpole in the DuPont courtyard on the MIT campus (see Figure 5) was the structure chosen for monitoring. Parameters monitored were accelerations at three points along the length of the flagpole, as well as ambient temperature. The data obtained by the system was made available in real-time and in archived format to clients anywhere on the Internet. Ultimately, the project aimed at creating educational tools for enhancing the understanding of structural behavior.

\textsuperscript{5} Sudarshan (2.002).
Although it was not properly a WSN project (sensors were wired to a data logger), the lessons learned are equally valuable and mimic the difficulties anyone wanting to deploy a WSN in an infrastructure might encounter: (i) installation of the sensors was a challenging task due to the height of the flagpole; (ii) sensor packaging was key to ensure reliable operation of the system; (iii) due to the high sampling rate of the accelerometers (100 samples / sec), the data acquisition server had to handle a large processing load and as result, was not able to handle data archival efficiently. A complex distribution solution had to be implemented; (iv) vast amounts of data were gathered and keeping this information in the database was very expensive. Therefore, at the end of each hour, data older than 24 hours was purged from the database and stored in a zipped file. Whenever data older than 24 hours was required for a database query, it was extracted on the fly from the zip archive and uploaded into the database. However, as Sudarshan (2.002) argues, a better solution would have been to store only the compressed wavelet coefficients of older data in the database. When a query of older had been made, approximate sample values could have been reconstructed from them. With this scheme, the amount of data to manage would have been reduced and queries would had been faster.

Figure 5: The MIT DuPont courtyard flagpole.
A shake table test\textsuperscript{6} 

In 2002-2003, Todd C. Radford, a graduate student at MIT, evaluated a WSN made of Crossbow MICA motes with a small shake table. He easily set up the sensors and found that they functioned adequately. However, he found that they had severe restrictions that limited their applicability to monitor physical infrastructure. These limitations were mainly:

- Lack of robustness of sensor nodes
- Lack of accelerometer sensitivity to sense typical infrastructure vibration amplitudes and frequencies
- Limited ADC sensitivity, resulting in losses of data

He concluded that with the current state-of-the-art of the Crossbow MICA motes - which were and still are the most popular wireless sensor nodes - WSN were not still viable for infrastructure monitoring.

The London Underground\textsuperscript{7} 

The London Underground Project refers to a Cambridge MIT Initiative (CMI) 2.003 project to use WSN to support construction works during the construction of a new tunnel as part as of the Channel Tunnel Rail Link (CTRL), Section II, in London.

The project required the measurements of displacements of an existing tunnel (the Circle Line, one of the oldest tunnels of the system) while the construction of a new tunnel, almost perpendicular, underneath. The new tunnel was being bored using a Tunnel Boring Machine (TBM) and had to pass underneath by 10 meters, at a rate of 40 meters per day.

Obviously, the new tunnel could cause settlements in the Circle Line. However, the London Underground Office expected to be able to operate the

\textsuperscript{6} Radford (2003).
\textsuperscript{7} Song (2004) and Cheekiralla (2004).
existing line during construction works. Displacements could not exceed the critical value that forces the tunnel to be shutdown.

In this context, the CMI installed a wireless sensor network to measure the linear displacement and deformation from the closest station in real time. If the displacement was greater than 5mm, London Underground office would stop the operation of the Circle Line. The construction work for the CTRL line was expected to take place 24 hours a day and continuous monitoring was needed.

16 Wireless sensor units were placed in October 2003 in the critical section along the tunnel to measure vertical displacements and traverse deformations. The data was organized into TCP/IP packets, sent through the Internet, archived, and published using web services. Figure 6 shows a graphical schema of the Project.

![Graphical schema of the London Underground project. Courtesy of Song & Cheekiralla, (2004)](image)

According to the project reports, the main lessons learned were: (i) the ADC of the MICA motes (10-bits) did not have enough resolution to detect very
low vibrations such as ambient traffic disturbance; (ii) a lot of processing had to be done due to data losses (faulty communication or interferences caused by passing trains or environmental changes) and noise levels in the readings; (iii) real-time monitoring was not possible because the data had to be processed before the displacements could be calculated.

The Alamosa Canyon Bridge

This is a project undertaken by the Department of Civil and Environmental Engineering at Stanford University (2001) and it's, to the best of my knowledge, the most promising real-world deployment of WSN for structural monitoring so far, benchmarking wired systems.

The project consisted on the instrumentation of the Alamosa Highway Bridge in New Mexico with wireless sensing units and MEMS accelerometers. The goal was to monitor the bridge's response to modal hammer blows and traffic loads (see Figure 7). The system recorded the bridge response to forced vibrations and every sensing unit executed fast Fourier transforms to identify the primary modal frequencies of the bridge. To benchmark the performance of the wireless system, a commercial wire-based monitoring system was also installed.

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The tests revealed the following findings: (i) the WSN monitoring system was capable of collecting sensor data with high precision; (ii) the bridge first three modal frequencies were accurately determined; and (iii) the installation of the wireless monitoring system was completed in approximately half the time required by the commercial wired system. Therefore, it was concluded that the wireless system was as reliable and accurate as the tethered (wired) monitoring system.

**Technological challenges**

Common patterns arise from the projects just described. They encountered similar difficulties, which can be summarized as follows:

- Weak packaging
- Limited ADC resolution
- Power consumption too high
- Range too short
Communication latencies
Data loses

Technology improvements will solve the packaging, ADC sensitivity, battery life, and range issues in the near future. However, the others are more difficult to solve. Research in this area is currently focusing on providing: (i) Reliable data-transport to overcome the high packet loss rates; (ii) Low-overhead data-time-stamping; and (iii) Wavelet-based compression techniques (Xu et al., 2004).

Conclusion

This Chapter has described the main drivers that push WSN into structural health monitoring. WSN promise to overcome the current limitations of wired systems and help infrastructure owners to both guarantee the public safety of structures and to optimize the money spent on maintenance and repair. Then, it has listed the characteristics such a WSN should have, and it has being showed that the latest research-based deployments have had very promising results (e.g. The Alamosa Bridge project). However, practical ("commercial") wireless sensor networked structural health monitoring systems are several years away (Xu et al., 2004).

The final is "to have a smart city where all structures could react to catastrophic events such as earthquakes and natural corrosions in hopes of improving public safety and reconstruction costs" (Greene, 2001. p.16), an ‘intelligent city’ where danger can be pinpointed and emergency response directed with precision" (Rough, 2001). We can imagine the following scenario:

“Data from buildings and its surroundings is collected by sensors, and transmitted in real-time to a centralized cluster of servers using wireless transmission. The signals are then processed to remove noise and test inconsistencies and fed to a fast simulation model. The results from the simulation are then processed to determine if correction action needs to be taken. If so,
actuators on the building are triggered to control its displacement, or, in the case of emergencies, the appropriate emergency personnel are immediately notified” (Sudarshan, 2002. p.11)
4. THE AEC INDUSTRY AND THE INNOVATION OF WSN

Introduction

The previous two Chapters have provided us with an understanding of the technological aspects and characteristics of WSN in order to be used in Civil Engineering. Together they form the first ‘building block’ of this Thesis.

In this Chapter we'll focus our attention on the context in which we intent to use WSN. It's the second ‘building block’ of this Work. We want to understand the 'rules of the game' in the AEC industry, so we can provide a realistic and viable roadmap to innovate through WSN.

The Chapter is structured as follows. In first place we'll describe the characteristics of the AEC industry. Then we'll focus on innovation, and explain the motivations and driving forces that push for it. We'll also describe the types of innovation with special emphasis on one of them (Christensen's disruptive vs. sustaining innovations). Finally we'll come back to the AEC industry to analyze how innovation takes place within it. We'll describe the innovations and opportunities WSN may bring.

The AEC industry

Understanding the AEC industry and the forces that affect it is the first step if we want to be able to predict its future.

Characteristics

The main traits of the construction industry are given next (Ber, 2003):

- Huge industry. It represents in average around 10% of a country's GDP and workforce.
• Highly fragmented and volatile due to the small size of the average organization.
• 4 different market segments: civil infrastructure; residential buildings; non-residential; buildings; and repair and maintenance.
• Highly cyclic and dependent on public spending (roughly 50% of the total market share)
• Every project is unique, a “prototype”, which forces to adapt each time resources and construction methods to local conditions. It also makes more difficult to reach economies of scale.
• The production process is carried on “in situ” instead of in a manufacturing plant. Therefore, it’s dispersed and under the influence of local geographic and meteorological conditions. Production is also usually located distant from human and materials resources.
• The building process is long. Therefore, it’s more affected by external events and changes in the initial conditions.
• From the very beginning to the end of the building process, there’s a high interaction with the customer (owner). Customer personality plays a great role.
• The final price is defined at the beginning of the process and it is a fixed variable. Therefore, the dependent variable is the cost, which is affected by resources availability, changes in prices, etc.
• A great variety of materials and parts is managed, usually in large quantities. Besides, there are multiple organizations involved in an average project.
• High turnover and low educated workforce. Labor-intensive. This is a major cause of the lack of skilled professionals, low productivity and high accident rates.
Competition

Porter's model of competitive forces provides us with a very powerful tool to analyze the industry. According to Maloney & Hancher (1997), the five forces can be analyzed as follows in the AEC industry:

- High threats of entry:
  - There are not existing economies of scale
  - There's very few differentiation on the product of engineering and construction organizations. However, there's differentiation on the service provided.
  - Capital requirements are low because practically all assets can be leased
  - The switching cost for customers are low
  - Intellectual Property (IP) consist mainly of engineer's knowledge and experience. Therefore, it's very difficult to keep it as a proprietary asset because personnel move easily between firms.

- High internal rivalry
  - There are numerous and equally balanced competitors. Competition is a zero sum game. In other words, it destroys average profitability
  - Slow industry growth. Then, growth must come at the expense of competitors, and it's very costly to gain market share this way (usually the only way is lowering prices, which brings us to the previous point)
  - The product is perceived as a commodity, which causes a very high competition on prices and service.

According to Michael Porter, author of two of the most cited business books (Competitive Strategy and Competitive Advantage), five forces can be identified that determine an industry profitability: (1) the entry of new competitors; (2) the threat of substitutes; (3) the power of buyers; (4) the power of suppliers; and (5) rivalry among the existing competitors.
- Many substitute products: Almost every product in the AEC marketplace can be substituted by another one, which places an upper limit on the prices firms can charge (and thus their profitability).
- High bargaining power of buyers: Due to the way that engineering and construction work is awarded (usually design-bid-build) buyers have a lot of negotiating power and put a lot of pressure on prices. Alternative contract forms have not substantially changed this situation.
- Low bargaining power of suppliers: There are usually many potential suppliers available competing to serve engineering and construction firms.

Digital intensity

Since innovation is mostly driven by New Information Technologies (NIT), it is also useful to understand the digital intensity of the AEC industry. The framework of digital transformation in traditional businesses developed by Andal-Ancion, Cartwright & Yip (2003) is a very appropriate tool to analyze the digital intensity of the construction sector. There is no doubt that construction is a traditional industry.

This framework makes use of 10 different drivers. Each of them is very specific to how NIT can be applied to a particular industry. It will help us to better understand the relationship between technology and the industry. The drivers are:

1. Electronic deliverability: some products have a large component that can be delivered electronically. In the AEC industry we encounter both extremes. On one hand architects and engineers who can deliver their product and service through electronic means (e.g. product specifications, design notes and blueprints). On the other hand the final product (e.g. a building) that cannot be delivered electronically.
2. Information intensity: nearly all products and services have some information content. In the AEC industry the final product includes very few information. It is mostly as-built plans.

3. Customizability: the degree of customization of an offering to the specific needs and preferences of individual customers. In our industry we have a high degree of customization. Every product is unique.

4. Aggregation effects: Products and services differ in the way they can be aggregated or combined. There is a high degree of aggregation since it is common to find organizations that to manage the entire product cycle (design-build-maintain) for their customers.

5. Search costs: the difficulty of finding the product, its features and service attributes. These costs are low in the AEC sector.

6. Real-time interface: it deals with how important information changes suddenly and unpredictably. It's not important in construction where time frames are from days to years.

7. Contracting risk: the degree to which it is necessary to see, touch, and try a product to buy it. This is very high in construction. Architects usually want to see materials textures and colors before they approve them. In addition, new technologies like 3D visualization are making this driver more important.

8. Network effects: Sometimes the utility of a good or service increases with the number of people who are using it (or one that is compatible). There are no network effects in our industry. The only exception is the software used by the industry (e.g. design, planning, and estimation software) and perhaps knowledge management.

9. Standardization benefits: the more standards the business processes and products specifications, the easiest it is to synchronize them. The standardization in the AEC industry is currently very low although the benefits would be enormous.
10. Missing competencies: the degree to which one organization depends on others within a value chain. This degree of dependency is very high in construction (e.g. contractors and subcontractors)

The drivers fall into three categories are showed below in Figure 8.

![Figure 8](image)

**The 10 Drivers of New Information Technologies (NIT)**

<table>
<thead>
<tr>
<th>Type of Driver</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inherent characteristics of product or service</td>
<td>1. Information intensity</td>
</tr>
<tr>
<td></td>
<td>2. Customizability</td>
</tr>
<tr>
<td></td>
<td>3. Electronic deliverability</td>
</tr>
<tr>
<td></td>
<td>4. Aggregation effects</td>
</tr>
<tr>
<td>Interactions between company and its customers</td>
<td>5. Search costs</td>
</tr>
<tr>
<td></td>
<td>6. Real-time interface</td>
</tr>
<tr>
<td></td>
<td>7. Contracting risk</td>
</tr>
<tr>
<td>Interactions between company and its partners and competitors</td>
<td>8. Network effects</td>
</tr>
<tr>
<td></td>
<td>9. Standardization benefits</td>
</tr>
<tr>
<td></td>
<td>10. Missing competencies</td>
</tr>
</tbody>
</table>

Figure 8: The 10 drivers of NIT. Andal-Ancion et al. (2003)

It can be concluded that the main drivers in the construction industry considered as a whole are customizability, high contracting risks and standardization benefits.

**Technological innovation**

**The case for technological innovation**

Innovation has become a buzzword these days. But, why?; what is the motivation to innovate? There are many reasons. Perhaps the most important are: (1) innovation has substituted production as a key driver of competitiveness; (2) innovation is a driving force of economic growth.

Because of these, innovation activity is a major concern of firms and even governments. At a firm level, innovation may become key to a firms' competitive advantage beyond the traditional drivers of cost, quality and time. It is becoming
a major competitive tool to gain market share and better profitability (Seaden, Guolla, Doutriaux & Nash, 2003). Therefore, organizations need a continuous flow of innovation to (Oslo Manual, 2002):

- Replace products being phased out
- Extend product range
- Develop environment-friendly products
- Maintain market share
- Open up new markets
- Improve production flexibility
- Lower production costs
- Improve product quality
- Improve working conditions
- Reduce environmental damage

However, innovation is risky. It requires significant investments and is often resisted. We have to keep in mind that to innovate is to change and that is never easy (Seaden et al., 2003).

A definition of technological innovation

According to the Oslo Manual (2002), technological innovation can be defined as:

“Technological product and processes (TPP) innovations comprise implemented technologically new products and processes and significant technological improvements in products and processes. A TPP innovation has been implemented if it has been introduced on the market (product innovation) or used within a production process (process innovation). TPP innovations involve a series of scientific, technological, organizational, financial and commercial activities. The TPP innovating firm is one that has implemented technologically new or significantly improved products
or processes during the period under review” (Oslo Manual, 2002, p.31).

In other words, we can define innovation as the successful introduction in the marketplace of any kind of new ideas and knowledge, either as a product or service, or as a combination of both. Therefore, innovation is purely a business activity. It does not have to be confused with invention, which refers to ideas or concepts for new products or processes (Utterback & Acee).

Types of technological innovation

There are two main kinds of innovation: innovation by products and innovation by process. Innovation by products means searching for completely new products or services, or the improvement of existing products or services. The Oslo Manual (2002) defines it as follows:

“A technological new product is a product whose technological characteristics or intended uses differ significantly from those of previously produced products. Such innovations can involve radically new technologies, can be based on combining existing technologies in new uses, or can be derived from the use of new knowledge”. (Oslo Manual, 2002, p.32)

On the other hand, innovation by process means the improvement of production methods to obtain the same final product (Moron, 2004). The Oslo Manual (2002) defines it as:

“A technological process innovation is the adoption of technologically new or significantly improved production methods, including methods of product delivery. These methods may involve changes in equipment, or production organization, or a combination of these changes, and may be derived from the use of new knowledge. The methods may be intended to produce or deliver technologically new or improved products, which cannot be produced or delivered using conventional product methods, or
essentially to increase the production or delivery efficiency of existing products". (Oslo Manual, 2002, p.32)

In addition to this classification of innovation, Taylor & Levitt (2004) propose another. According to them, an innovation can be either of a systemic nature or localized. Systemic innovations are those that require multiple specialist firms to change their processes in a coordinated fashion. They enable significant increases in productivity over the long term and may create switching or start-up costs for some participants, reduce or eliminate the role of others. Examples of this innovation are virtual design and construction, supply chain integration, or prefabrication of component systems. On the contrary, localized innovations are those that imply change only within a specific specialty type. They reinforce the existing product or process and provide a measurable impact on productivity. An example of this type of transformation would be the transition from “stick-built construction” to prefabricated “wall trusses” in homebuilding.

**Christensen's Innovation Model**

It is also well known the distinction made by Christensen (2003) between sustaining and disruptive technological innovations. His distinction is very useful to us because his proposed innovation model argues that most disruptive innovations are bottom-up, attacking from below the incumbent technology paradigm. This is perhaps the case of wireless sensor networks technology in its current state of development.

Sustaining innovations are those that do existing things in a novel and better way. In other words, doing the same things than before in a more efficient way. On the contrary, disruptive innovations totally change the way in which something is done.

According to Christensen & Raynor (2003), in sustaining circumstances established components win the “battle” of innovation. They are better in improving existing products that can be sold for money to attractive customers. On the other hand, disruptive innovations are normally conceived outside of established organizations. In this scenario, a new incumbent will win the “battle”
commercializing a simpler, more convenient product that sells for less money and appeals to a new unattractive customer set. The innovation has the potential to turn established organizational or industry norms upside down, and to redefine the marketplace (Christensen & Raynor, 2003) (e.g. extending the market to a whole new class of customers).

There are three critical elements of disruption to be considered in this analysis. First, there is a rate of improvement that customers can utilize or absorb. Second, there is, in every market a, distinctly different trajectory of improvement that innovating companies provide as they introduce new and improved products. Finally, the third critical element refers to the distinction between sustaining and disruptive innovation:

“Sustaining innovation targets demanding, high-end customers with better performance that was previously available.”

[...] “Disruptive innovations, in contrast, don’t attempt to bring better products to established customers in existing markets. Rather, they disrupt and redefine that trajectory by introducing products and services that are not as good as currently available products”.

(Christensen & Raynor, 2003. p.34).

Additionally, there are two different types of disruptions to consider. In first place, there are those that create new markets. In other works, “constitute either new customers who previously lacked the money or skills to buy and use the product, or different situations in which a product can be used – enabled by improvements in simplicity, portability, and product cost”. In second place, there are low-end disruptions, which are those that target the least profitable and most over served customers at the low end of the customer’s segmentation (Christensen & Raynor, 2003).

In order to determine whether an idea has disruptive potential or not, they propose a set of questions to answer, grouped in three sets. The first one explores whether the innovation belongs to the first type of disruption: new-market disruptions. For this to happen, at least one and ideally both of the two following questions must be answered affirmatively:
• “Is there a large population of people who historically have not had the money, equipment, or skill to do this thing for themselves, and as result have gone without it altogether or have needed to pay someone with more expertise to do it for them?

• To use the product or service, do customers need to go to an inconvenient, centralized location?” (Christensen & Raynor, 2003. p.49).

The second set of questions explores the other type of disruption: low-end disruptions. This happens if the following two questions are answered affirmatively:

• “Are there customers at the low end of the market who would be happy to purchase a product with less (but good enough) performance if they could get it at a lower price?

• Can we create a business model that enables us to earn attractive profits at the discount prices required to win the business of these underserved customers at the low end?” (Christensen & Raynor, 2003. p.50).

The third set, once an innovation passes the precedent tests and it’s clear that it’s either a new-market or low-end disruption, includes only one question to answer affirmatively:

• “Is the innovation disruptive to all of the significant incumbent firms in the industry?” (Christensen & Raynor, 2003. p.50)

Another, perhaps clearer, way of determining if a technology is disruptive of not is analyzing if it meets the following criteria (J.M. Utterback, 2005):

• It has a lower cost than the incumbent technology

• It has a lower traditional performance than the incumbent technology

• It has a higher ancillary performance than the incumbent technology
Technological innovation and the AEC industry

Let's look now at the role that technological innovation plays in the AEC industry. As we have just seen, this industry is one of the largest in the world and is often described as a laggard in the adoption of the products and processes. It seems that the intrinsic characteristics of the industry inhibit innovation.

In fact, it is true that construction still has to capture the productivity gains achieved in the manufacturing industries with systemic invention like supply chain integration. However, at a "localized" level, construction innovates at a similar rate than manufacturing industries (Levitt & Taylor, 2004). An example of this can be found at the innovations in construction heavy equipment.¹⁰

From all the AEC industry characteristics, perhaps the most important is that work is done in a project-basis. As Levitt & Taylor (2004) have showed, it requires an extra effort to diffuse innovations across the industry. They provide a compelling example that illustrates their point of view: If in the transition from "stick-built construction" to prefabricated "wall trusses" in homebuilding there were, for example, five different contractors in a geographic area, it would take only five projects for the innovation to diffuse completely. This is due to the fact that the innovation is localized. On the contrary, in the case of prefabricated subcomponent wall (a systemic innovation), the lumber contractor, the plumbing contractor, the electrical contractor, and the mechanical contractor need to change their processes. If again there were five contractors for each specialty, that would result in 625 different combinations. As we can see, it takes 125 times more effort for a systemic innovation to diffuse completely. In their own words

"When organizational variety is high and the span of a systemic innovation increases to impact two or more specialist firms, extra coordination is required for inter-organizational knowledge to flow and accumulate. This explains why systemic

¹⁰ Other examples of innovation in the AEC industry can be extracted from Seaden et al. (2003): Computer-aided design (CAD); Laser-guided equipment; high performance concrete; composite materials (e.g. fiber reinforced plastics); deconstruction and reuse systems; pre-assembled air, water, power distribution systems; and Global Positioning Systems (GPS)
innovation diffuses more slowly than localized innovations in project-based industries" (Levitt & Taylor, 2004. p.12-13).

To promote innovation in the industry, Levitt & Taylor (2004) propose in first place organizational strategies like partnering and co-location of cross-disciplinary teams. In second place, they argue that the industry should promote the rapid creation of standards as common interfaces that would allow systemic innovations.

Macomber (2003) also believes that the structure (high fragmentation, therefore lack of a “channel master”) of the industry only promotes localized innovation and inhibits systemic innovation. Wondering why with widely available tools providing apparent improvement to design and construction processes, the industry does not change, he also concludes that the monetary implications are not well considered. As Macomber argues, there aren’t economic motivations supporting technological innovations in the industry. In other words, those who take risk innovating do not get appropriate compensations. Consequently, firms only innovate with technologies that will reduce their costs, not the overall system costs.

He provides the following example: A construction management firm may invest in high tech, state of the art tools. However, this firm is likely to be retained on some form of cost plus a fee contract. In this scenario, any savings generated with the new technology are not going to be retained in the firm but rather are going to be passed to the owner. Not only this, but if the design firms can manage the project costs down thanks to the new technology, its percentage based compensation would also go down. Then, why should this company bother to innovate? “Virtually everyone in the construction supply chain works on contracts where the incentive is to maximize their gain at the expense of others” (Macomber, 2003. p.8)

To Macomber, systemic innovations will come from new players with disruptive business models employing technologies that are too novel, too difficult, or too unappealing for the leaders to adopt for established firms - the classic Christensen’s “Innovators Dilemma” we have just described.
Benefits of WSN in structural health monitoring

Structural health monitoring is seen as the main application for wireless sensor networks in our industry. Why?

Current technologies for structural health monitoring are expensive and cumbersome. This is a consequence of the high installation costs associated with system wires - installation can represent up to 25% of the total system cost with over 74% of the installation time focused solely on the installation of system wires -. As an example, fiber optic monitoring systems cost between $20,000 and $100,000 for concrete bridges with spans of 200 meters. These high costs have slowed down the adoption of structural monitoring technologies in the marketplace. Only structures identified as critical justify the expenses of adopting a structural monitoring system (Lynch, 2002). Besides, in addition to being expensive to install, the cables can fail due to environment exposure or potential damage during extreme events. Long cables also result in sensor signal degradation (Straser et al., 2001).

On the contrary, wireless sensor systems eliminate the need of wiring and thus reduce significantly the deployment time. Moreover, they are made of off-the-shelf electronics components, therefore having a fraction of the cost of wired systems. Besides, wireless sensor units decentralize to a local level the process and interrogation of measured data, instead of doing it in a centralized server. This characteristic allows scalability of the system and a larger number of sensors on the structure. Finally, these systems seem to make feasible the shift from scheduled maintenance to condition-based maintenance, where inspection costs can be drastically reduced by 0.1% of the bridge’s total construction cost (Lynch, 2002).

But is there really a need for WSN-based structural health monitoring systems? To answer this question, we will focus on bridges. According to the National Bridge Inventory Study Foundation (NBISF, 2001), there’s a minimum of 600,000 bridges in the U.S. and one in four is considered deficient, two out of three do not have safety features meeting standards, and hundreds of thousands are in dire need of repair. In fact, nearly one in every four bridges is
recommended for replacement due to substandard load carrying capacity or substandard bridge roadway geometry (NBISF, 2001). The estimated improvement cost of U.S bridges is over $200 Billion but there’s not so much money available. So priority is given to scour critical bridges, which means that the foundation is in danger of erosion and the bridge could collapse. There are 20,000 scour critical bridges in the U.S. and improvement costs for these bridges, not just mitigation, would cost an estimated $7.8 Billion (NBISF, 2001).

The Federal Highway Administration mandates evaluation of condition of bridges every two years. Usually, visual inspections are done to spot symptoms of fatigue and damage, but do not detect inner failures (e.g. corrosion of internal steel reinforcement bars, fatigue cracking of materials, etc.). These schedule-base inspections cost between 0.05 to 0.1% of the total construction cost of the bridge (Lynch, 2002). Unfortunately, the large number of bridges combined with a small staff make this modest biannual period of bridge inspection not always achievable (Chang et al., 2003. p.258). When they are, they are rated according to their safety and reliability. But currently in the US, “more bridges are being replaced because they are functionally obsolete than because they are structurally unsound” (Chang et al., 2003). Worse, structural deficient bridges are not replaced, representing a serious threat to public safety.

So it seems there is a problem. The infrastructure is getting old and is becoming a potential serious threat. However, Society lacks the resources and will to address this issue. In addition, the scarce resources available are not optimized because there is a lack of knowledge about which structures need to be prioritized. Finally, repairing works in damaged structures is not optimal either. Only critical infrastructure justifies the expenses. Within this context, WSN can provide us with an effective solution. They promise to be accost-effective solution to continuously monitor and evaluate our infrastructure, and assess precisely the severity and location of damage. But, how are going to impact the current status quo of the AEC industry?
WSN: sustaining or disruptive innovation?

Following Christensen's methodology we will next answer the following question: are WSN a disruptive innovation or simply an evolution of existing technologies? To do this, we'll go step by step through Christensen's Innovation framework.

The answers to this first set of questions, which address the "new-market disruptions" are affirmative, so it can be concluded that WSN have the potential to become a "new-market disruption". Adoption of structural health monitoring systems has been low because of their high costs. Public agencies and private owners will undoubtedly be happy to see the costs of their systems go down and easier to deploy. In fact, infrastructure has been historically underserved. There is an urgent need of repair and maintenance. And nowadays the only solution is a combination of expensive monitoring systems, NDE tests, and expert structural engineers to interpret the data.

Let's move to the second sets of questions. The answer to the first question is already negative, so we can discard WSN as a low-end disruption.

At this point, there is one last test to pass: "is the innovation disruptive to all of the incumbent firms in the industry?" (Christensen & Raynor, 2003. p.50). The answer is negative. In a market research, incumbent firms have been identified as already having incorporated WSN to their offer (e.g. Smart Structures, Advitam Group). Therefore, it can be concluded that WSN, although having the potential for a "new-market disruption", will be a sustaining force rather than disruptive force.

Conclusion

This Chapter has analyzed what makes the AEC industry so specific, the nature and importance of innovation, and how it applies to construction. Next, it has analyzed the innovations that WSN bring to the area of structural health monitoring. It has showed that WSN will bring many benefits to the AEC industry. Finally, after an analysis using Christensen’s innovation framework, it has been
concluded that the innovation is more likely to be sustaining rather than disruptive.
5. APPLICATIONS

Introduction

Previous chapters have described the changes that are occurring in the crossroads of WSN and the AEC industry. It has been showed that WSN are a source of innovation. This Chapter translates these ‘changes’ and innovations into real world scenarios.

Basically, applications of WSN in the AEC industry can be divided between structural health monitoring applications and those that are not. The Chapter will briefly describe each of them. In the case of structural health monitoring, some scenario planning is done in the form of an Executive Summary.

Structural health monitoring

There are two basic scenarios for structural monitoring: extreme event (earthquake) and periodic monitoring, as it’s described in Straser et al. (2001).

Extreme event monitoring

The goal of extreme event’s monitoring is to provide infrastructure owners and government officials with a quick estimate of the amount of damage caused by extreme events (typically earthquakes). It’s based on measurements of the structure’s displacements or its derivatives.

In this scenario, the sensors are in background state, waiting for an earthquake. When one occurs, the sensors awake and data is acquired and stored during its duration. The data is then immediately analyzed to obtain quick indicators of the structure’s health.
Periodic monitoring

The goal of periodic monitoring is to identify the incipient deterioration of a structure. It’s based on the analysis of the structure’s modal properties. In its simplest form consists on discovering the vibrational properties of the structure. Little analysis is needed in this case: changes in the modal properties will alert engineers that some conditions have changed. On the contrary, on its most complex form, additional engineering expertise is needed, as well as the expected failure modes of the structure and mathematical models. A range of analytical techniques are used: fatigue analysis, fracture mechanics, finite elements modeling or sensitivity analysis.

There are two different scenarios for periodic monitoring: long term (permanent installations) or temporary installations. In the case of permanent monitoring, the sensor nodes are most of the time in sleeping mode and awake via an internal timer. When they do it, they perform a monitoring test, and then the system transmits the data for storage and analysis. This option also allows extreme event monitoring if the sensors are able to awake after recognizing the large signals of an extreme event. As compared to temporary installations, labor costs associated with installation are lower and errors in sensors placement are minimized. However, battery life becomes the weakest element in the system.

Temporary installations, on the other hand, are sensor installations that only last for a few days or a week, when several tests can be performed. This is a feasible option for non critical structures, where the expenses of a dedicated system are not justified. Infrastructure owners could use this approach to distribute the costs of a WSN between many structures.

An Executive Summary: e-Structures

Next there’s the Executive Summary that puts into practice the main ideas developed in this Thesis and the applications described in the previous paragraphs. It intends to provide a compelling example of how a particular institution (in this case the Massachusetts Institute of Technology, perhaps the
most entrepreneurial Institution in the world) can innovate using WSN and obtain an economic benefit. Some of the details are fictitious.

This Executive Summary is based on the work by Ber & Aw (2005). It's also inspired in Sensametrics, Inc. (http://www.sensametrics.com), a start-up based in Palo Alto, California, and founded by researchers from the University of Stanford. Sensametrics is currently the market leader in providing wireless sensor networks for structural health monitoring and according to its web page, its mission is “to be the World leader in Nervous Systems for Buildings and Structures" [...] providing a complete global and cost-effective structural health monitoring network for civil assets”

eStructures Executive Summary

Description of business

Bridge failures are national disasters, can cost human lives and affect badly a country’s reputation. And yet, the US Department of Transportation admits that 15% (92,112) of the total 614,083 US bridges are close to collapse, and 28% (171,943) are under allowable standards. In the next years, $200 billion are needed to be invested in order to improve the nations’ bridge inventory.

e-Structures aims to provide a low cost, state of the art wireless monitoring system to monitor the health condition of bridges. It's a technology that has been developed at the Massachusetts Institute of Technology and is currently being patented. The solution is modular and has the potential to be used in other areas such as dams, high rise structures, tunnels, water pipes etc. It addresses the need of critical infrastructure continuous monitoring and provides a scientific-based framework to optimize maintenance and repair budgets, and save thousands or millions of dollars to infrastructure owners.

e-Structures aim to be the leading provider worldwide of low cost monitoring solutions to all civil structures.

Opportunity and market overview

From a total of 614,083 bridges in the US, there are 171,943 substandard bridges, and 92,112 of those are in critical state. The estimated improvement costs are well over $200 billion. Supposing this amount of money is invested in a 20 years time frame then $10 billion are expended annually in bridge maintenance and repair. Assuming than 1% of this money is spent in monitoring and inspection previous to design and construction work, there's a $100 million market for the e-Structures solution only in the bridge segment. Moreover, this is an expanding market since bridges always need continuous monitoring by law and they become older every year. We plan to capture 25% of this market in 5 years with our revolutionary technology and expand later to other market segments.

Current monitoring solutions are expensive and difficult to install. Therefore the main inspection method for bridge health assessment is through visual inspections. However, this procedure relies too much on the inspector judgment and do not detect dangerous inner failures (e.g.: corrosion of internal steel reinforcement bars, fatigue cracking of materials). E-structures solution overcomes these uncertainties and, allows designers and engineers to rapidly identify the location and severity of structural damage. Thus, budgets for infrastructure maintenance and repair can be optimized, which results in savings of thousands or millions of dollars to infrastructure owners. Using e-Structures solution is cost-effective on repair projects with a $3 million budgets. Besides, engineers will also be able to design more reliable and economic structures, minimize catastrophic failures in the construction process and evaluate the effects of construction on adjacent structures.

The product offering

e-Structures provides a low-cost off-the-shelf infrastructure monitoring solution based on a decision support software and a high-density wireless sensor network with diverse types of MEMS-based sensors. Sensors are to be deployed on the structure surface. They gather critical data that can be analyzed with our proprietary software. This software package is compatible with the most popular software for AEC design.

A working prototype has been developed and installed on a bridge in parallel to a commercial cable-based monitoring system. Testing of the bridge has revealed the wireless monitoring system to be as reliable and as accurate as
the existing wired monitoring system. But when wired systems costs an average of $60,000 for concrete bridges with spans of 200 meters, e-Structures solution costs half this price tag and cuts in half the deployment time while keeping similar or better performance.

The average sale is estimated at $30,000 which includes hardware installation and a software license. Each wireless sensor node will be priced at $500 while the software license will be priced at $10,000. The production cost for each sensor is approximately $50 since it is made of off-the-shelf electronic components.

Business strategy

e-Structures business model would shift from a service/consulting firm with a direct sales approach during the first two years to a product company (software + hardware) with an OEM sales strategy through partnerships with established engineering firms.

E-Structures team will focus on the design of the sensing unit and wireless sensing network, develop embedded damage assessment algorithms, and a decision support software. Hardware manufacturing will be outsourced with the assistance of Millennial Net.

Our customers are the top 100 ENR Engineering firms. We plan to close partnerships with at least the top 10 in the U.S. like Bechtel and GBH Engineering during the first two years of operation. With our solution these companies would gain a competitive edge when bidding for contracts, as well as be able to extend the range of services they offer to their customers.

The main revenue will come from the hardware sales and software licenses. Additional revenue will come from training on the use of our solution and how to interpret the data.

Our marketing strategy is simple and effective, and is based in advertisement in a combination of advertisement in specialized magazines and presence in the major industry conferences.

Competition and competitive advantages

e-Structures will have to face competition from both existing firms in the AEC sector as well as from new players willing to enter this new market.

Existing hardware manufacturers of sensing and monitoring devices like PCB Piezotronics or Bridge diagnostics are the main competitors. These companies will certainly oppose a fierce resistance since our offering is a direct
competitor to their products. These firms are relatively small and their offering cannot compete in price or deployment speed to our solution, which delivers the same results at half the price and deployment time. Consequently, they'll probably lower their prices and will play the card that their technology is proven and effective. However, our patented technology, MIT brand and scientific presence on the Board will certainly assure our clients.

Additionally, competition would also come from new players like Crossbow, MicroStrain or Smart Structures. Crossbow and MicroStrain are both producers of wireless sensor networks hardware with existing solutions for civil and structural health monitoring, although their products do not fulfill yet the requirements of a structural health monitoring system and they do not offer any specialized engineering service or software to analyze the data. Smart structures, on the other hand, it does offer an integrated solution for bridge monitoring, but seems to lack behind in using wireless sensors, and relaying more in wired sensors. A possible scenario would be one where Smart Structures partner with one of the hardware manufactures mentioned to offer an integrated wireless solution. To offset this case, e-Structures has to secure rapidly partnerships with the major engineering firms and build a brand associated with scientific rigor.

The competitive advantage of e-Structures will come from its patented technology and ultimately from its technology leadership. Moreover, e-Structures is currently the only firm with a working integrated solution covering hardware, decision support software and structural engineering expertise.

Financial prospects

The financial prospects for the first five years of operation are summarized below. More details can be found at the business plan.

<table>
<thead>
<tr>
<th>Year</th>
<th>Market Share</th>
<th># kits sold</th>
<th>Revenue (millions)</th>
<th>Expenditures (millions)</th>
<th>Profits (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0%</td>
<td>12</td>
<td>$ 0.36</td>
<td>$ 1.00</td>
<td>$(0.64)</td>
</tr>
<tr>
<td>2006</td>
<td>2%</td>
<td>60</td>
<td>$ 1.80</td>
<td>$ 1.44</td>
<td>$ 0.36</td>
</tr>
<tr>
<td>2007</td>
<td>6%</td>
<td>240</td>
<td>$ 7.20</td>
<td>$ 5.76</td>
<td>$ 1.44</td>
</tr>
<tr>
<td>2008</td>
<td>13%</td>
<td>500</td>
<td>$ 15.00</td>
<td>$ 12.00</td>
<td>$ 3.00</td>
</tr>
<tr>
<td>2009</td>
<td>25%</td>
<td>1000</td>
<td>$ 30.00</td>
<td>$ 24.00</td>
<td>$ 6.00</td>
</tr>
</tbody>
</table>
**Financing**

In order to proceed e-Structures anticipates the following funding needs over the next two years:

- $0.6 million in Production Costs
- $0.6 million in Research and Development
- $0.4 million in Marketing and Sales
- $0.3 million in General and Administrative expenses
- $0.1 million Legal expenses

Therefore s-Structures is seeking $2 million in VC funding for the next two years of operation. Breakeven point is expected in 3Q of year 2 of operations with $1.8 millions in revenues. An additional $3 million of financing is expected to be needed to finance an aggressive market segment and international expansion. The exit strategy will be to get acquired by a major engineering firm like Bechtel, a manufacturer of sensing and monitoring devices like National Instruments, or an accredited and independent major quality assurance firm or laboratory in civil engineering like Froehling & Robertson.

**Milestones**

The milestones are summarized below. As we have mentioned before we have a working prototype and a patent in progress.

- **2006:** Hire Sales force and develop distribution channel. Deploy our solution in at least 60 bridges. Close partnerships with top 10 ENR Engineering firms. Execute marketing plan.
- **2007:** Raise 2nd round of financing to finance rapid growth and expansion to other markets (e.g. skyscrapers) and countries (Western Europe and Japan).
- **2008-2009:** Continue rapid growth. Initiate contacts with potential buyers. Capture 25% market share or $30 millions in revenues.
Team

We are currently in the process of putting together the ideal team for this company. We pursue candidates with similar background to those described below. In the meanwhile co-founder Jordi Ber would act as CEO.

- **CEO:** A former Principal in an ENR 100 Engineering Firm. Successful background in growing rapidly a company. Must provide strong industry connections.
- **CFO:** 10+ years of experience either in the financial sector working at prestigious investment banks, or in the AEC industry working at infrastructure project financing.
- **VP Marketing and Sales:** 10+ years of experience in the Product or Software Industry for the AEC Sector. Must provide strong industry connections.
- **COO:** Jordi Ber. Co-founder. Jordi holds both a Master of Science in Civil Engineering from ETSECCPB, Barcelona (Spain) and a Master of Science in Management from HEC Paris, Paris (France). He is currently a CEE MEng candidate at MIT. He has two years of experience in the AEC industry.
- **CTO:** Eng Sew Aw. Co-founder. Eng Sew holds a Master of Science in Civil Engineering from MIT and is currently a PhD candidate at the same institution.

We also plan to include on the Advisory Board some Professors from MIT that had supervised the Research Project that has led to this solution and business opportunity. They would contribute to strength the technical foundation of the Company and provide key contacts

**Other applications for WSN in the AEC industry**

WSN can also be smartly integrated in construction materials and processes in the AEC value chain.

**Monitoring during construction**

Monitoring can begin at the construction stage. As Hudson (2.002) argues, there are many reasons for this:
• Reduce costs: Monitoring devices can be used to:
  o Provide early alerts of possible failure, thus avoiding the need for contingency plans
  o Pinpoint more easily the source of a problem and make easier to implement a correction
  o Determine the best time to perform a task (e.g. in excavating procedures or when staying fill layers on embankments)
  o Determine when to stop a task and help in scheduling (e.g. determine when a pile or beam has reached its bearing capacity)
• Improve safety, providing early alerts.
• Maintain quality: Monitoring devices can be used to check assumptions made during the design stage (e.g. site conditions) but also provide an accurate proof of the quality of work of a contractor.
• Minimize liability: Instrumentation data can help in the accurate assessment of damages induced by a particular construction activity, or responsibilities between different parties in a contract.

Next we provide some cases where WSN could be applied during the construction process

**Construction Quality Control**

Wireless sensor networks could also have a great impact in construction quality control tests, reducing the time and costs needed to perform these tests. With the appropriate sensors, applications in this area could be almost endless. Three examples are provided next:

**Bridge Load Test**

Existing wireless sensor networks have currently, as we have just seen, two major advantages over existing wired systems: reduced cost and reduced

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12 Xu et al. (2004)
deployment time. However, they have one major drawback, which is the lack of a sustainable energy source. Existing WSN prototypes for structural monitoring only last from some hours to a few days.

Having said this, we can think of a situation where we can benefit from the WSN advantages without suffering from its limitations. Such a case would be that of the load test for a new bridge. Before the bridge is open to traffic, few days can be committed to measure its structural properties. A WSN could be deployed in a few hours, while it would take weeks to do so with a wired system. Then engineers would force a vibration to get some measurements (e.g. a large truck crossing the bridge). Since the challenge is often knowing where to deploy the sensors - because the structural characteristics are not known - the ability to move easily sensors from one place to another would make this process much easier.

In such a scenario, two parties would get an immediate benefit: the owner and the bridge designer. The owner would, in first place, be sure that the bridge is safe. Secondly, it would have a structural model of the behavior of the real bridge (as compared to the designed one), which he will be able to compare against in some years ahead, and have an exact measure of the bridge's deterioration. On the other hand, the designer will receive direct feedback on his design and use this knowledge to improve and optimize future designs. (Xu et al., 2004).

**Smart Piles**\(^\text{13}\)

Smart Structures, Inc. is a spin-off from University of Florida that plans to use wireless sensor networks to measure stresses on concrete piles used in foundations. The idea is very simple and consists in the casting of a wireless sensor package directly into wet concrete piles. When the piles are driven into the ground, the sensor sends wirelessly, in real-time, the load capacity (see

\(^{13}\) http://www.smart-structures-inc.com & University of Florida (2004b)
Figure 9). With such a system, engineers are capable of monitoring the structural integrity of the project.

Smart Structures claim that the cost of its wireless sensors is less than one-tenth the cost of a typical load test. Consequently, a 100% of the piles in a foundation can be monitored for approximately the same cost as testing 10% of the piles with current testing methods. It’s also claimed that using its smart pile system, construction time can be reduced.

The Concrete Maturity Method

The Concrete Maturity Method is a proven, non-destructive concrete's strength estimation technique. It was originally developed in the late 40's and early 50's. It consists on using time and temperature measurements to determine the strength gain of in-place concrete. This method brings some advantages as compared to other destructive tests (as cited by King, 2005)

- It accelerates construction schedules and therefore helps to reduce costs (e.g. by allowing earlier form removal)
- Improves Quality Control, providing real-time concrete strength and recording temperature evolution.

WSN facilitates the adoption of the concrete maturity method. Sensors can be easily been embedded in the structure, attached to the steel bars. Once the concrete is poured, they monitor the temperature and real-time concrete strength can be obtained through the use of established relationship curves

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14 King (2005)
(maturity °C-hours vs. compressive strength psi). These curves are mix-specific and are calibrated by sample cylinder break previous to construction.

**Extend design firms' range of services**

Innovative design firms should consider paying a close attention to the developments of WSN technologies and acquire an expertise in the uses of this new technology. This would allow them to expand their scope of services and differentiate their value proposition, which is key in the AEC Industry competitive environment.

In first place, design firms could leverage WSN to penetrate into the repairing and maintenance market segment, which is the fastest growing segment in the marketplace. Using WSN they could optimize repairing and maintenance costs for their clients, thus gaining a competitive edge in their bidding processes. In second place, they could make use of the Observational Method\(^{15}\) approach in more projects, using WSN for monitoring.

**Enhance construction products**

WSN would soon allow adding a virtual layer of “intelligence” to existing construction products, expanding their features and increasing the value for customers. The most evident example is that of precast / prestressed concrete products like beams, girders, pipes, etc. We can, for example, think of a manufactured prestressed girder for a bridge that, once under service, automatically informs about its structural behavior. Is it behaving as expected?

\(^{15}\)“The Observational Method is a continuous, managed, integrated process of design, construction control, monitoring and review which enables previously defined modifications to be incorporated during or after construction as appropriate. [...] The objective is to achieve greater overall economy without compromising safety”. (Nicholson, D., Tse, C-M. &. Penn, C. (1999). The Observational Method in ground engineering: principles and applications. CIRIA.
We can also imagine pipes that automatically inform whether they have broken wires or not, making possible to quickly locate leaks. This compares, for example, to the current state of practice with electromagnetic inspections of prestressed concrete cylinder pipes (PCCP). Inspections have to be carried out walking through the pipes at scheduled outages with a sensor and data acquisition system mounted on a cart. Then, the data acquired is post-processed (Ojdrovic, 2005).

**Integrate construction and facilities management**

There's a growing trend in the marketplace for a closer integration between the construction and operation phases of a facility lifecycle. Contractors are moving into facilities management, offering their customers an integrated range of services. Within this context, WSN are going to provide infrastructure owners with another reason for a closer integration between the construction and operation phases of their physical assets. In first place, there will be an additional layer of sensing and monitoring devices that will need to be incorporated to the construction process. Secondly, someone will have to manage the data collected by these networks. Contractors are well positioned to fulfill this role. We have to keep in mind that new information and knowledge about our buildings and facilities that was not available before is going to come up to the surface. Someone will use it to offer new value added services regarding operation and maintenance.

**Conclusion**

If WSN succeed in delivering their promises, the entire construction value chain will benefit. Owners will probably reduce total project costs, obtain precise measurements of the quality of construction, and own safer assets (e.g. an alarm fires when certain parameters are exceeded). Contractors will benefit by being
able to better balance cost and quality, therefore optimizing the use of equipment, materials and labor. Designers will be able to validate design tolerances and optimize safety factors, thus reducing the size of elements and construction costs, and consequently reduce total project cost. Finally, sensor's data will enable to minimize renovation and maintenance costs, as well as maximizing structures' useful life.

There are many opportunities for entrepreneurs and fast-moving established firms in the crossroads of WSN and construction. This Chapter has pinpointed some of them but probably the uses for WSN that are most likely to succeed are yet to be discovered. The value that WSN are bringing is not in the hardware – it quickly become a commodity - but in the new data these networks are going to make available.
6. CONCLUSIONS

Summary and conclusions

Wireless Sensor Networking (WSN) is a new and promising technology, based on recent advances in telecommunications, computing and sensing. A WSN consists of a network made of several small electronic devices (or nodes). Communication takes place wirelessly, often in a peer-to-peer fashion. WSN allow a spatio-temporal understanding of an environment. They can be used to monitor space, to monitor objects, and to monitor the interactions between those objects and their surrounding environment. Applications of this technology are almost end-less. However, technology is not yet mature enough and has yet to deliver on their promises, mostly on reliability.

Civil Engineering is one of the many fields where WSN have raised some expectations. So far, research has mainly focused on structural health monitoring. As it has been analyzed in this Thesis, WSN will solve the main problems of existing wired systems: high cost and poor scalability.

In addition to structural health monitoring, WSN can also be applied in different situations during the construction process. They can be a source of feedback to the designer, be embedded in construction products, or help to control and improve the construction process. Some examples have been provided.

It can be concluded that, once WSN will be more mature, they will certainly bring many improvements to the AEC industry. According to Christensen's framework on innovation, these improvements will be in the form of sustaining rather than disruptive innovations. WSN main advantage will be a substantial reduction in the cost of deploying monitoring devices. Having said that, the amount of data that these networks are going to bring up to the surface will be something new. It's in this data where the value of these networks will
reside. Unfortunately, the question of what to do with it remains unanswered and should be explored in further work.

**Afterword: the role of Civil Engineers in sensing**

WSN pose a very interesting question. As we have seen, sensing and monitoring systems involve a great variety of knowledge and areas of expertise that do not fit into the traditional concept of civil engineering. Some civil engineers feel that this area should be left to people with electrical, computer science, or even mechanical backgrounds. This would be a major mistake because civil engineers would miss some opportunities and the profession would loss attractiveness. Civil Engineering has, thanks to WSN, the opportunity to rethink how things are being done and expand to promising new areas of work.

As Radford (2003) says, there are other compelling reasons for civil engineers to get involved in sensing. First, civil engineering systems tend to be different from other systems. Secondly, they require specific knowledge (e.g. structural design), thus making the civil engineer the most qualified professional to deal with sensors in infrastructure monitoring. Thirdly, sensing systems for civil applications are large-scale distributed systems. Therefore, again, civil engineers are uniquely positioned to confront this situation.

We can then see civil engineers as experts in infrastructure, both physical (the bridges and the roads) and virtual (the IT-based nervous system of existing infrastructure, made of the sensors data measurements). Sensing is simply the link between both worlds (Radford, 2003).

Because of this, every firm in the AEC Industry should follow the advances in WSN to anticipate future events. As pointed out in this Thesis, innovation may become key to a firms’ competitive advantage beyond the traditional drivers of cost, quality and time. AEC firms must invest in Information Technologies (IT) in order to not “miss the boat”. The role of civil engineers will certainly change as we progressively add a layer of intelligence (virtual infrastructure) to
the existing one.

In the long term, as Roush (2.001) points out, legions of tiny, wirelessly interconnected sensors will be mixed into building materials, such as concrete or bricks (see Figure 10), to provide a continuous report on a structure's physical state.

Figure 10: A vision for the future: The smart brick
REFERENCES


