Building Technology Trends and Their Implications Regarding Technology Management in the Buildings Industry

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ABSTRACT

In the next few decades to come, two trends in building system technological evolution are likely to contribute to making buildings more efficient and comfortable. These trends are: the infusion of "computer-on-a chip" microchips into all manner of energy consuming devices, and the proliferation of miniature devices made using the same techniques used to make semiconductor microchips. The use of these technologies will also result in more technologically complex buildings, which will likely pose new challenges for those organizations that design, build, and operate buildings. After all, the capability of these organizations to manage technology has as much or more influence on actual building performance as does technology. Furthermore, there is ample evidence that many buildings organizations are already stressed by their efforts to manage complex technologies that exist today. It remains to be seen whether these challenges are actually mitigated by further technological advancement, new buildings organizations with increased capabilities to manage complex building technologies will emerge, or buildings organizations will continue to operate with technology management capabilities that are comparable to those they currently exhibit.

Introduction

Between 1979 and 1995, the amount of energy consumed per square foot of U. S. commercial building floorspace declined by 21 percent. Although this index is an imperfect means to measure building energy efficiency—for example, it does not take into account changes in the weather, building occupancy patterns, economic activity, the mix of fuels consumed, and the quality of services provided by building systems—it probably represents a substantial improvement (Energy Information Administration 1998). Undoubtedly, technological progress was one the numerous factors that propelled that improvement.

Given that technological progress is likely to continue at a frenetic pace, it is equally likely that advancements in building system technologies will contribute to similar efficiency improvements over the next few decades to come. I expect two building technology trends to be especially important over this time period: the infusion of networked miniature computers into all manner of devices contained within buildings; and the increased use of the same processes applied to produce microchips to manufacture miniature mechanical devices for use in buildings.

If these trends do come to pass they will likely lead to far more technologically complex buildings. Such an outcome concerns me, as there is ample evidence that many of the organizations that design, build, and operate buildings are already facing significant challenges as the endeavor to manage complex technologies that exist today. It remains to be seen whether these challenges are actually mitigated by further technological advancement, new buildings organizations with increased capabilities to manage complex building technologies will emerge, or buildings organizations will continue to operate with technology management capabilities that are comparable to those they currently exhibit.

A Computer in Every Air Conditioner

Last summer the National Semiconductor Corporation unveiled a new computer chip that puts most of the functions of a personal computer on a single chip. Nicknamed “a system on a chip,” this chip does the work that before required six different chips, including microprocessors, memory, graphics, and communication. Combining these functions on to a single chip reduces both the size and the cost associated with PC-like computing capabilities, which makes it possible to incorporate these capabilities into more products. So far, National Semiconductor is developing these chips for use in information appliances such as television set-top boxes, palm pilots, and car navigation systems. I can foresee the day, however, when “computer on a chip” chips are embedded into all kinds of building systems, linking them to networks, enabling communication between systems, diagnosing problems, and providing far better control than we enjoy today.

For a good example of how these miniature embedded computers will make buildings more efficient and comfortable, consider how microprocessors are currently improving the operation of comfort refrigeration systems. Contained in most air conditioning units, these systems are operated using relatively simple minded controls (**Figure 1**). The compressor turns on and off based on a signal from a room thermostat, and the expansion valve opens and closes to maintain a constant temperature difference between the evaporating temperature and the temperature of the vapor leaving the evaporator. This temperature difference is known as superheat, and it serves as a safety factor to ensure that the refrigerant in the suction line is always sufficiently warm that it remains in the gas phase. Note that there are no feedback loops between these two control systems, so each operates as though the other didn’t exist.

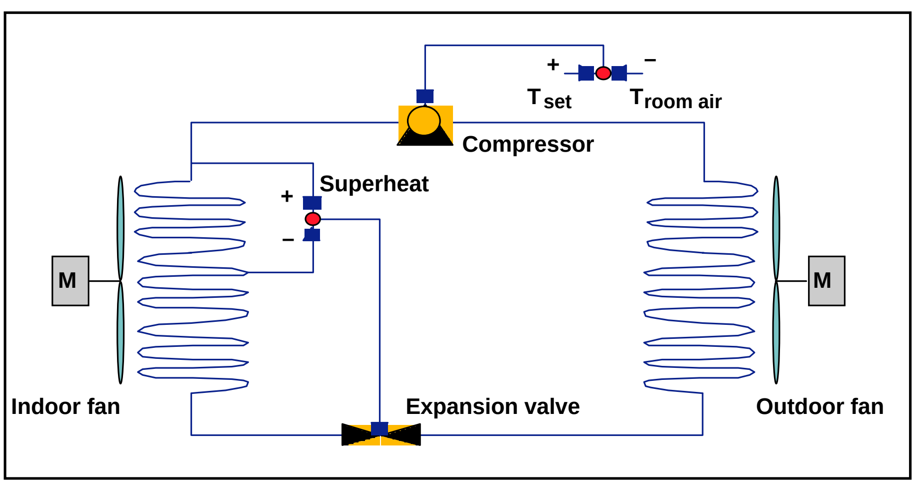

Figure 1: A Basic Comfort Refrigeration System

A big problem associated with this control strategy is that whenever there is a change in compressor operation, expansion valve operation becomes unstable for awhile, and the superheat fluctuates widely. To compensate for this problem, manufacturers make the superheat setting high enough so that no matter what happens, the compressor won't be damaged by trying to compress any unevaporated liquid refrigerant. That protects the compressor, but at the cost of decreased system efficiency. This control scheme is safe, and inexpensive, but it is slow to respond and inefficient.

A much better way to control this system would be to coordinate compressor speed and valve opening area to match the system's cooling output with the actual thermal load. This sort of control strategy is much more stable, and because it is more stable, the superheat control can be set to a much lower temperature, which improves efficiency.

This strategy is called multi-input multi-output control, because the control system makes decisions based on multiple information input streams, and sends output signals to both the compressor and the expansion valve. Developed by a team of MIT scientists, this control system depends on a complicated sequence of algorithms and requires an onboard microchip to do the calculations (He et al. 1998).

When those scientists tested their control strategy on a residential air conditioner, the air conditioner responded much faster to changes in compressor operation and operated more efficiently. Under conditions that took the conventional single-input single output control system 4 to 6 minutes to reach stable operation, the multi-input multi-output system took only about 2 minutes. Furthermore, cutting the superheat setting from 18°F to 9°F saved about 10 percent of the system's overall energy consumption (He et al. 1998).

So far multi-input multi-output control has only been incorporated into a single product: a 3.5 ton packaged air conditioner, which is manufactured by Daikin and sold only in Japan. In this example, the microprocessor only enabled better communication and control between control loops contained within a single device. The impact will be more profound when multiple interacting devices employ miniature computers to communicate and orchestrate their actions.

For example, consider the chilled water systems that are used to cool large commercial buildings. In 1989, the last year that such data is available, the U.S. Energy Information Administration estimated that such systems in the U.S. consumed 30 billion kilowatt-hours of electricity (Energy Information Administration 1994). A single variable-air-volume chilled water system might contain hundreds of single-input single-output loops to control compressors, fans, pumps, and dampers. If embedded miniature computers enabled these systems to become even 10 percent more efficient, which is the improvement achieved by multi-input multi-output control, their impact would be considerable. It is likely that other building systems would benefit similarly from such interactive control.

Big Things Come in Small Packages

Photolithography, the technique that is used to manufacture semiconductor chips, is increasingly being used to mass produce mechanical devices with exceedingly tiny dimensions. These devices, which are known as *microelectromechanical* systems, may have dimensions as small as a fraction of a millionth of a meter. They are fabricated into a host of miniature devices analogous to full size devices already used in buildings, including motors, temperature and flow sensors, valves, batteries, and fuel cells. As these devices are introduced into buildings, they are going to provide far more customized energy services than their macro-scale predecessors were ever capable of.

Take for example, a miniature refrigeration system under development at the University of Illinois. This device is actually a little vapor compression refrigerant system, designed to fit into a 4 inch square package, just slightly smaller than a compact disc case. Just like an ordinary refrigeration system, it will contain a compressor, an evaporator, a condenser, and an expansion valve. The refrigerant will probably be HFC-134a. These micro-coolers will be mass produced by building them up, one thin-layer at a time using flexible polymer materials, designed specifically for this application. Although each individual cooler will provide just a bit less than one-thousandth of a ton of cooling, they will be joined together into sheets that provide whatever amount of cooling is necessary.

The researchers at the University of Illinois expect that when they are first massed produced, these coolers will be about as efficient as ordinary refrigeration systems, and will cost about \$5 to \$15 each. That’s about 10 to 30 times the cost of an ordinary room air conditioner today. Given this difference in price, it’s clear that these micro-coolers aren’t going to replace their full-sized predecessors overnight (Shannon 1999).

At first, micro-coolers will be used to provide targeted cooling. The military is funding their development in order to produce air-conditioned uniforms for soldiers who are suited up for biological and chemical warfare in hot climates. During the Gulf War about 10 years ago, the U.S. army found that soldiers overheated quickly when they wore gas masks and protective clothing in the desert. Eventually, micro-coolers will likely find their way into the civilian market where they will be used to cool electronic equipment, car seats, water bottles, vaccines, operating room workers, clean room workers, firemen, and overnight packages.

Over the long term, if mass production enables their cost to drop low enough, much as it has done for semiconductor chips, micro-coolers have the potential to solve a big problem in buildings. In most air conditioned buildings, cool air is produced in a central location and then distributed throughout the building by a network of ducts. This design has two inherent problems: the pipes and ducts waste a lot of energy and their ability to distribute thermal energy is fairly limited. People frequently complain that the part of the building they occupy is either too warm or too cool. Some studies report that one-third to one-half of the office workers questioned find their offices to be too hot or too cold (Kempton & Lutzenhiser 1992). A building that was conditioned by a distributed network of micro-coolers attached to ceilings, walls, partitions, and perhaps even seats, could feature a profusion of small temperature zones, each with a different setting selected by its occupant. Not only would such a system save energy, but it would enhance occupant comfort, and by doing so, improved productivity would likely follow.

To Make Things Even More Complicated

Imagine for a moment a building filled with micro-coolers, each containing a miniature computer, and all of them in constant communication, coordinating their efforts to optimize efficiency and thermal comfort. Such a building would provide far more effective and efficient comfort services than contemporary buildings, but at the expense of far greater complexity.

Now consider this question: Who is going to maintain this building? Just because a building contains technologies designed to enhance both efficiency and comfort doesn't mean that building will be efficient and comfortable. The ability of organizations that design, construct, and maintain buildings to manage those technologies strongly influences their performance. It is becoming increasingly apparent that many buildings industry organizations—including architecture, engineering, contracting, and maintenance firms—are already stressed by their efforts to manage the complex building technologies that exist today. How will these organziations manage the vastly more complex buildings that are likely to exist in the future?

This issue was exemplified recently at the Pacific Northwest National Laboratory, in Richland, Washington, where two office buildings with the same floor plan were built side-by-side. The only important difference between the two was that the second to be built incorporated several energy efficiency technologies that the first did not, such as low-emissivity windows, T-8 lamps, carbon dioxide sensing ventilation control, and premium efficiency motors. When the buildings were occupied, the second building used less energy than the first, but after four years of operation it consumed 40 percent more energy than its ostensibly less efficient counterpart. The second building also generated many more occupant discomfort complaints.

When the two buildings were monitored, investigators found that the second building's problems were largely due to operator errors. Most importantly, the operators in the second building had manually overridden that building's computerized controls, compromising its ability to automatically adjust temperature setpoints. For example, the operators set cool air supply temperatures so low that the building's controls called for energy-intensive mechanical cooling even on cool days when just the economizer cycle should have been sufficient. Furthermore, several static pressure sensors were malfunctioning, which caused several large fans to run at full speed when reduced speed would have been sufficient. These malfunctioning sensors were not diagnosed and replaced by the operating staff. Although the operators' mismanagement of the control system probably did not compromise the performance of the efficiency technologies that distinguished the first building from the second, that mismanagement wasted far more energy than those technologies were capable of saving (Lettau & Morasch 1999).

The situation at the Pacific Northwest twin office buildings is far from being an isolated case. One need only review the proceedings of the annual commissioning conference sponsored by Portland Energy Conservation, Inc. to find many more similar anecdotes. As contemporary buildings industry organizations are challenged by even more complex technologies, three outcomes seem possible:

1. That systems containing profuse networks of microelectromechanical devices with embedded miniature computers will actually compensate for undertrained designers, installers, and operators.
2. That new buildings industry organizations will emerge that are far more capable than contemporary organizations of managing complex technologies.
3. That buildings industry organizations will continue to operate with complex technology management capabilities that are relatively similar to that which they currently display.

These three outcomes are not mutually exclusive, and it is possible, if not likely, that the actual outcome will embody elements of all three.

Thinking Machines to the Rescue

Perhaps buildings systems containing embedded miniature computers and microelectromechanical devices aren't the problem, but instead are the cure. Maybe they will allow undertrained designers, installers, and operators to succeed by eliminating the need for expert human diagnostics or sophisticated installation and repair techniques in the field.

Consider what might have happened had the twin Pacific Northwest office buildings contained a cooling system composed of micro-coolers with embedded computers. Such a system would have provided such sophisticated control and diagnostic services that it might have simply self-corrected without any operator intervention, or suggested solutions to the operators that were more effective than overriding the automatic controls. Furthermore, the control system would have identified any micro-coolers that contained faulty components, leaving the operators with the simple task of removing several inexpensive micro-cooler modules and replacing them with new ones. Lastly, the ductwork whose malfunctioning sensors eluded the Pacific Northwest operators would have been eliminated altogether.

Smarter Organizations Carry the Day

Perhaps, contemporary buildings industry organizations can learn how to better manage complex technologies by studying successful *high reliability organizations*. Long examined by academics, high reliability organizations manage technologies that are so complex and hazardous, were they to make any technical errors, great public harm could result. As a result, virtually all high reliability organizations are subject to some form of intrusive public oversight. Common examples of high reliability organizations include utility grid managers, the air traffic control system, and flight operation crews aboard U.S. Navy aircraft carriers. These characteristics make high reliability organizations excellent laboratories in which to study technology management techniques (Rochlin 1993).

By comparing examples of successful high reliability organizations with accounts obtained from accident investigations, researchers have concluded that the successful organizations make a greater effort to collect reports of failures and conduct a richer analysis of the data they gather. Because the ability to learn from trial and error is limited in high reliability organizations, the successful ones compensate by making the best of those opportunities that do occur. They have learned that even a minor problem could be an indication that other portions of the system are inoperative or malfunctioning.

To increase the amount of information available for learning, effective high reliability organizations encourage employees to report errors. They have determined that the value to the organization of remaining well informed and aware of the potential for error far outweighs any benefits that might be gained from punishing individuals or deflecting criticism (Weick et al. 1999).

For example, Wernher Von Braun, the former director of NASA's Marshall Space Flight Center, once rewarded an engineer with a bottle of champagne after that engineer reported that he may have damaged an electrical circuit during the pre-launch testing of a missile that crashed. The investigation that ensued concluded that the circuit had been damaged and that did cause the missile to go out of control. By revealing his mistake, the engineer helped his organization avoid the expense of redesigning the missile (Weick et al. 1999).

In another example, an investigator found that the highest performing nursing units reported higher error rates for adverse drug events than did lower performing units. Her interpretation of these results were not that more errors were made in the high performing units, but that the open reporting of errors made it possible for workers to learn from them and to work towards minimizing them (Weick et al. 1999).

This practice stands in stark contrast to that of organizations that design, build, and operate buildings. In these organizations, errors are typically isolated and denied. This mode of operation was typified by several of the contractors who worked on the University of Chicago Graduate School of Business Building. When this building was completed in 1995, an investigation revealed that its heating and air conditioning system suffered from numerous flaws, which included:

1. The ventilation system was moving about 30 percent excess air;
2. At least one major zone was receiving only about half of its design air flow; the building automation system was reporting that all air flows were at design levels, though they demonstrably were not;
3. Duct work connected to all the air flow volume control boxes leaked; and
4. Many fan motors were locking out on overheat safety control (Wolpert et al. 1995).

It took well over a year to correct these problems, as well as others, at considerable expense. When some of the contractors who worked on the building were later questioned by the owner regarding how such problems could be avoided on subsequent projects, several of them denied that their companies needed to make any changes. They insisted that even though the building suffered from the flaws listed above, and others, that their companies had met the terms of their contracts. They suggested that the University was at fault for testing their work (Stein et al. 1995).

Another way high-reliability organizations increase their opportunities for organizational learning is by placing great emphasis on collecting and analyzing the observations of the maintenance department. This makes a great deal of sense when one considers that in a technologically centered organization, maintenance personnel are typically on the front line. They experience more failures at earlier stages of development than any of the other departments, and often have a better understanding of technological vulnerabilities, sloppy operations, procedural gaps, and the consequences of multiple interacting errors. Most buildings industry organizations, however, act as though the observations and wisdom of maintenance departments are of little value.

For example, in the Pacific Northwest National Laboratory building discussed above, the maintenance workers responded to comfort complaints by taking actions that resolved those complaints in the short-run. They either did not know or did not care that their actions degraded the efficiency of the overall system and led to problems in other parts of the building. Implicit in their actions was their belief that the system as it was designed to operate was not capable of maintaining adequate thermal comfort, and that the value of the energy that was wasted by off-design operation would not otherwise be allocated by higher decision makers towards upgrading the system.

Such behavior and beliefs are probably widespread in the buildings industry. Once when I was consulting for a large telecommunications company, I had the opportunity to interview one of their maintenance workers regarding opportunities to improve maintenance practices in order to reduce energy waste. Although he was pleased to help, he insisted that my efforts would fail. He reasoned that since his managers had ignored his ideas regarding such opportunities for decades, it was unlikely they would listen to me either. As it turned out, he was right.

Clearly, buildings industry organizations can only emulate high reliability organizations in limited ways. These latter organizations face far more dangerous missions than buildings industry organizations, and as a result, many of the techniques they employ are so expensive, that any buildings industry organizations that attempted to incorporate them would be unprofitable. There is reason to believe, however, that the techniques discussed above can be adopted in ways that enhance buildings industry organization profitability. One profitable business organization, although not in the buildings industry, that seems to have incorporated some of the learning techniques used by high reliability organizations is Chevron, the oil company.

In the early 1990s, after Chevron benchmarked itself against competitors and found itself lacking, management decided to focus on internal benchmarking and disseminating best practices as a means to catch up. Since energy expenses account for 30 to 40 percent of an oil refinery's operating budget, it didn't take long before improving energy performance became a major focus point. At each refinery, Chevron appointed a team of energy coordinators who measure energy consumption, benchmark that consumption against a corporate index, and take responsibility to meet performance targets based on those benchmarks. To help them meet those targets, the coordinators share their best practices in a database that they can access via the Internet. Although, unlike high reliability organizations, they are not sharing their errors, but at least they are sharing their successes. Using this system, Chevron has reduced its overall energy consumption by about 18 to 20 percent, which is worth nearly $200 million a year (Nelson 1999).

Business as Usual

The ability of contemporary buildings industry organizations to manage complex technologies has been set by the market, and as such, is the result of interactions between millions of people over many years. Perhaps, the market is telling us that this is the level of competence that it is willing to pay for, and that is likely to remain relatively the same, as long as energy has a similar impact on corporate bottom lines, regardless of the technologies employed.

Provided that the potent combination of computers on a chip and microelectromechanical devices doesn't eliminate the need for highly trained designers, installers, and operators, will the capabilities of buildings organizations to manage complex technologies continue to limit the efficiency of buildings? Maybe, but markets also respond to new information. Perhaps in the future, research will clearly establish a link between occupant comfort and productivity. The link between productivity and corporate profits is already well understood. As in the Pacific Northwest twin buildings example, the same problems that diminished efficiency also led to greater occupant discomfort. Should the link between comfort and productivity ever be demonstrated in a compelling manner, buyers may very well demand more comfortable buildings, and in the bargain gain more efficient building.

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