A DECISION-SUPPORT FRAMEWORK FOR THE DESIGN AND APPLICATION OF RADIANT COOLING SYSTEMS

Shouib Nouh Ma'bdeh

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Architecture and Design Research

James Jones
Elizabeth Grant
Georg Reichard
Robert Schubert
Andreas Limberg

October 31st, 2011
Blacksburg, VA

Keywords: Radiant Cooling Systems, Decision-Support, Building Performance Mandates, Decision Mapping

A DECISION-SUPPORT FRAMEWORK FOR THE DESIGN AND APPLICATION OF RADIANT COOLING SYSTEMS

Shouib Nouh Mabdeh

ABSTRACT

Creating a sense of place through a comfortable indoor condition is a goal of the architectural design process. Thermal comfort is an important component of this condition. To achieve thermally comfortable environments mechanical systems such as Radiant Cooling (RC) could be used. RC systems have potential benefit of lower energy consumption when compared to other common cooling, ventilating and air-conditioning systems. Decisions related to the use of mechanical systems such as these should be considered in the early stages of design to maximize the building performance through systems integration and minimize redesign as part of the design process.

RC systems have several special demands and related variables. Architects, HVAC system engineers, and decision-makers have to understand these issues and variables and their impact on the other building performance mandates. Through this understanding, these professionals can better evaluate tradeoffs to reach the desired solution of the design problem. Unfortunately, in the United States few architects and engineers have experience with RC systems which in turn limits the application of these systems.

Through systematic literature review, a series of case studies, and interviews with experienced professionals, this research captures and structures knowledge related to how decisions are made concerning RC systems. Through this knowledge capturing procedure, the relevant design performance mandates, barriers and constraints, and potential advantages and benefits of radiant cooling systems are determined and mapped to a decision-support framework. This framework is graphically presented which may later be translated to a decision-support software package which could then be developed as a radiant cooling system design assistance tool for architects and HVAC engineers.

Dedication

In the memory of my father, Dr. Nouh Al-Qudah

The one who inspired me the most…

The one who taught me to keep learning and never quit…

The one whom I miss the most while I am finishing this journey…

I also dedicate my work…

To my Mother, her praying, encouragement, and constant love have sustained me throughout my life…

To the love of my life and my wife, Lubna Shihadeh, for her understanding, patience, and care…

To my beloved sister, Sukaina, and to my brothers, Dr. Ali, Dr. Mohammed, Dr. Haroun, Dr. Adam, Dr. Ismail, Bara, Anas, Owais, and Mohannd Alfaqeer…

You all are the best supporting team ever…

Acknowledgements

"*Whatever of good befalls you, it is from Allah*" (Quran, chapter 4, verse 9)

All Praise is due to Allah, to Whom all good things belong. Without His guide and blessing this work would not be happened.

I would like to thank my supervisor, Dr. James Jones, for his continuous guidance and assistance. I cannot express gratitude enough for his editing, counsel, patience, and honesty. Thank you Jim for everything.

I would also like to thank the members of my committee, they brought a unique and helpful viewpoints to improve the clarity and quality of this work. Thank you Dr. Elizabeth Grant for your critical thinking comments and your friendship. Thank you Dr. Georg Reichard for your clear and plain comments. Thank you Prof. Robert Schubert for your support and help. Thank you Eng. Andreas Limerg for answering my technical questions.

A special thanks to Dr. Edward Fox for providing me a space in his Digital Library Lab when my school abandoned its PhD students. He treated me as one on his students and made me feel home by inviting me to his lab social events. A special thanks to Chriss Mattsson-Coon for being the most wonderful and helpful person in the university. Another special thanks to Ahmed Kamal, as our continuous discussions were very helpful and fruitful.

I am also very thankful and grateful to Dr. Saher Lahour and his lovely family, Afek, Adam, and Amen, for giving me and my wife the feeling of being part of their family. A special thanks to Zakariya Dalala for being a true friend, to Abdessattar Abdelkefi and Sameh Ben Ayed for their care and support. I also would like to thank my father and mother in-law for their continuous support and help. A special thanks to Mohammad Al-Smadi, Rafe Marashdeh, Mohammed Aloshan, and Bandar AlKahlan for their friendship and support.

Many thanks for my colleagues and friends in Blacksburg and Jordan who cared and supported me in the time of hardship and difficulties, thank you all.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Overview

One of the main outcomes of the architectural design process is the creation of aesthetically pleasing, functional, and comfortable indoor conditions, where comfort is related to acoustical, visual, thermal, and air quality issues. It could be argued that among these issues, thermal comfort is most important when high performance HVAC operation and energy efficiency are goals. Providing acceptable indoor thermal comfort conditions means maintaining the indoor operative temperature within a range where occupants are neither warm nor cold - As defined by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) thermal comfort is “That condition of mind which expresses satisfaction with the thermal environment” (ANSI/ASHRAE 55 2004; ISO 7730 2005). Following the heat balance approach, which is based on laboratory studies of young healthy adults, there are six primary factors affecting the thermal condition: air temperature (ºF), radiant temperature (ºF), relative humidity (%), air speed (f/s), metabolic rate (met), and clothing insulation (clo). Whereas following the adaptive model approach, which is based on field studies, “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort. Therefore, self-regulatory actions will take place. There are three main sorts of self-regulation: physiologically adaptive, psychologically adaptive and behaviorally adaptive” (Yao, Li, and Liu 2009).

Before the industrial revolution, most works of architecture were designed to passively respond to the surrounding environment in various ways in order to create acceptably comfortable indoor conditions. In hot climate regions, for example, one of the most important issues is to keep the indoor environment acceptably cool, while warming the space is the primary issue in cold climates. However, after the invention of the mechanical refrigeration system and its adaptation to buildings around the turn of the 20^{th} century, architects were given the opportunity to move away from climate responsive strategies and space conditioning became more reliant on energy intensive solutions.

Today, there are many systems used to maintain thermal comfort in buildings. These include all-air systems, hydronic or water systems, and combined air and water systems. In the U.S. for non-residential buildings, air or air and water systems are fairly common because they couple space conditioning with ventilation. However, as an alternative and promising systems to these heating and cooling systems, hydronic or radiant systems have the potential to provide enhanced thermal environment while having economic benefits such as consuming less energy relative to all-air systems.

Radiant systems can be used for heating and cooling purposes. In the heating mode the system provides energy to the space through radiation, and in the cooling the system absorb the excess energy, mainly by radiation, and remove it from the space. Operating the radiant system at the cooling mode is more critical than at the heating mode; as the system heating capacity is, typically, larger than its cooling capacity, and the condensation issue. For this, this research focuses mainly when operating the system at the cooling mode.

The adaptation of radiant cooling (RC) systems in the U.S. has been relatively slow when compared to the European building sector. A main reason for this slow penetration to the U.S. building sector is the lack of educational and demonstrational tools for the design and application of RC systems mainly from an architectural point of view.

This research is providing a framework, mainly for architects, HVAC engineers, and decision-makers in the building sector, to help them when considering the use of RC systems in new designs.

1.2 Radiant Cooling Systems: Background

1.2.1 Introduction

Cooling and heating by active radiation is not new. One of the oldest active radiant cooling systems was found in the Kurdish settlement of Nevali Cori in eastern Turkey, dated 9000 years ago. “The cooling systems consist of an intermediate space below the floor, which in summer could be flooded with water from a nearby creek” (Feustel 1999). This water would lower the temperature of the floor thus absorbing heat from the occupied space mainly by radiation.

The Romans developed an active radiant heating system 2000 years ago, called a hypocaust, which means ‘heat from below’ (Kennedy 1985). The hypocaust system was based on a raised floor where hot gases or air distributed underneath would cause the floor to heat up and radiate heat to the occupied space. Muslim engineers improved the system during the 12th century using pipes carrying hot water underneath the floor instead of hot air or steam (Kennedy 1985), as water has more thermal capacity than air.

The first known modern radiant heating system was developed by Arthur H. Barker in 1907 when he embedded small hot water pipes in concrete to form a very efficient heating system (Stetiu 1998). The system became more common after Frank Lloyd Wright used it in his Johnson Wax Building in 1937.

At that time, thoughts were given to use the system for cooling purposes by running cold water instead of hot. However, most of these early attempts failed due to condensation problems on the cooled surfaces and due to the lack of proper ventilation to keep the surface temperature above the dew point temperature. Successful examples of a ventilation system and RC panels were used in a department store built in 1936-1937 in Zürich, Switzerland and in a multi-story building built in the early 1950s in Canada (Stetiu 1998).

All-air or air and water systems are the most common heating and cooling systems for non-residential applications in the U.S. The extensive usage of all-air systems brought with it many problems and issues such as sick building syndrome (SBS), increased energy consumption, and problems related to thermal comfort. For these and other reasons engineers and architects are now reconsidering RC systems for their advantages over all-air systems.

1.2.2 Definition and fundamentals

RC as defined by Moore, Bauman, and Huizenga (2006) is an active system which uses “cooled surfaces to absorb excess thermal energy and remove it from the space… [Then], heat is removed by chilled water flowing through a hydronic circuit thermally coupled with the surface.” This heat flow from the space happens primarily by radiation and secondarily by convection. As long as the temperature of active cooled surfaces are lower than the other objects within view of the cooled surfaces and the ‘hot’ surfaces have radiant emitting properties, heat will flow from the higher temperature surfaces to the lower temperature surfaces within the line of sight.

The radiant heat transfer by emittance is governed by the Stefan-Boltzmann equation, (ASHRAE 2009) :

$$W_b = \sigma T^4 \qquad \text{Eq. (1.1)}$$

Where:
W_b: The total energy emitted per unit time per unit area of a black surface to the hemispherical region above it
σ: (Stefan-Boltzmann constant) $0.1712 * 10^{-8}$ Btu/h·ft²·°R^4 (R: Degrees Kelvin)
T: The absolute temperature of the black body

However, for a nonblack body surface, the emissive power (W) at temperature T radiated to the hemispherical region above it is given by the following equation:

$$W_b = \epsilon \sigma T^4 \qquad \text{Eq. (1.2)}$$

Where:
ϵ: is the total emissivity of the nonblack body surface, (ASHRAE 2009)

Conroy and Mumma (2001) explained that in the case of radiant ceiling panels "for most building enclosure cases encountered in practice, the enclosure emittances are about 0.9, and the view factor between the ceiling and the balance of the enclosure is at least 0.87. Placing these common values into the Stefan-Boltzmann equation (Eq. 1.1) results in the following equation (ASHRAE 2009):

$$q_r = 0.15 \times 10^{-8} [(t_p)^4 - (AUST)^4] \qquad \text{Eq. (1.3)}$$

Where:
q_r = radiant cooling, Btu/h·ft²
t_p = mean panel surface temperature, °R (K)
AUST = area weighted average temperature of the non-radiant panel surfaces of the room, °R (K). Normally this means that the air temperature (ta) is about this temperature as well, particularly in cases where the design conforms to ANSI/ASHRAE/ IESNA Standard 90.1-1999" (ASHRAE 2009).

In addition, the cooling convective heat transfer which occurs in the boundary layer just below the panels is given by the following equation (ASHRAE 2009):

$$q_c = 0.31(t_p - t_a)^{0.31}(t_p - t_a) \qquad \text{Eq. (1.4)}$$

Where:
q_c: convection cooling, Btu/h·ft²
t_p: mean panel surface temperature, ˚F
t_a: air temperature, ˚F

1.2.3 RC systems; names and types

During the literature review, it was noticed that there is no consistency in the naming for RC systems. In many situations, researchers and manufacturers mix the names with confusing results. However, this section explains the different RC systems while trying to provide a definition and name for each system that is used in this research.

Moore, Bauman, and Huizenga (2006) categorized RC systems as either chilled slab systems or chilled panel systems. Stetiu (1998) categorized them into four different types:

a) Panel systems built from aluminum panels; Figure 1.1 and Figure 1.4.
b) Chilled slabs; Figure 1.2, Figure 1.6, Figure 1.7, and Figure 1.8.
c) Cooling grids of plastic tubes embedded in plaster or gypsum board; Figure 1.3.
d) Air-radiant floor system, where cooled air is circulated underneath the floor before being released at the perimeter for space ventilation. The cooled floor will absorb heat, mainly through radiation, from the space, and loses it to the cooler air circulating in the slab. Hot air could be used during the winter, Figure 1.9.

This research categorizes RC systems according to their location; in the ceiling, in the floor, or in the walls. However, as a study limitation this research discusses ceiling and floor systems as they are the most used types among all other RC system types.

1.2.3.1 RC cooling system types according to their location

a) In the ceiling; suspended or mounted as shown in Figure 1.1.

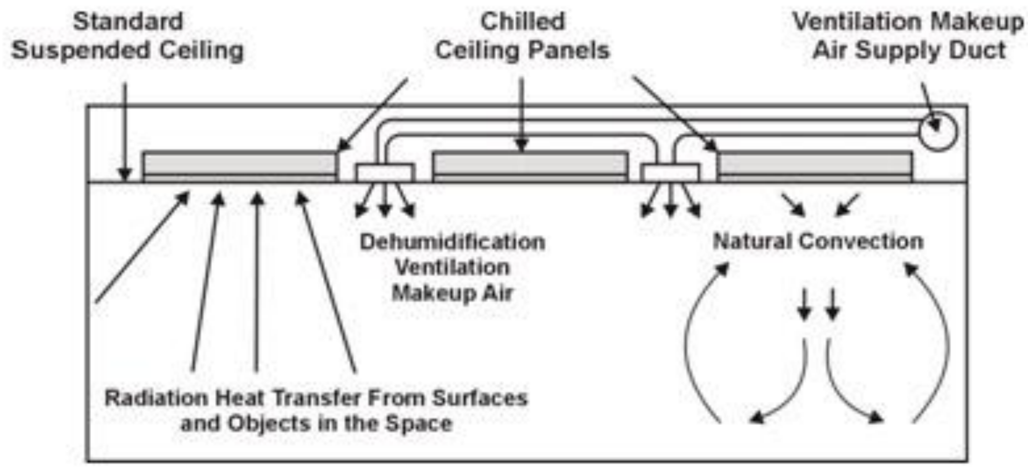


Figure 1.1. Schematic drawing of a radiant cooling ceiling system (Mounted panels)
Source: (Energy Efficiency Office of the Electrical and Mechanical Services Department 2009)

b) In the slab; the pipes are embedded in the slab as shown in Figure 1.2.

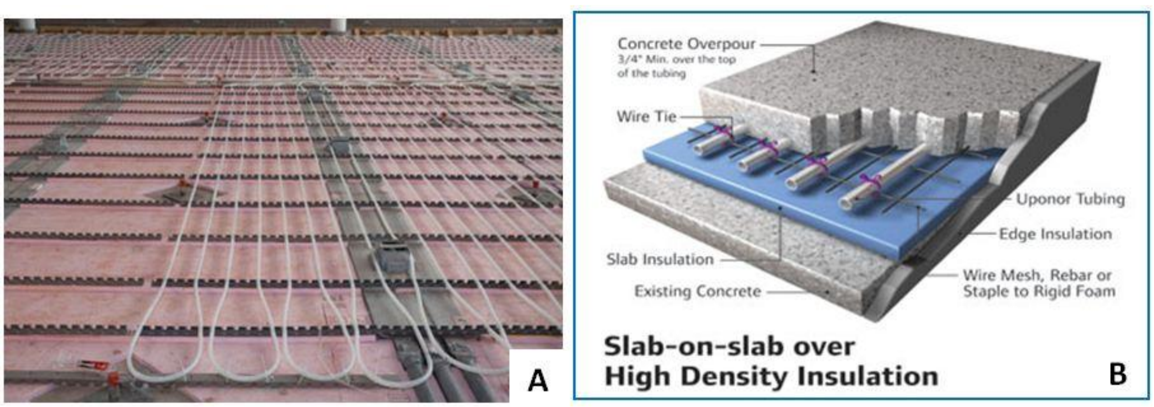


Figure 1.2. Chilled slab system; Typical installation (A). Floor details with RC system (B).
Source:(Uponor 2009)

c) In the walls; the pipes are attached or embedded in the walls, covered with plaster, or exposed to the interior space, as in Figure 1.3.

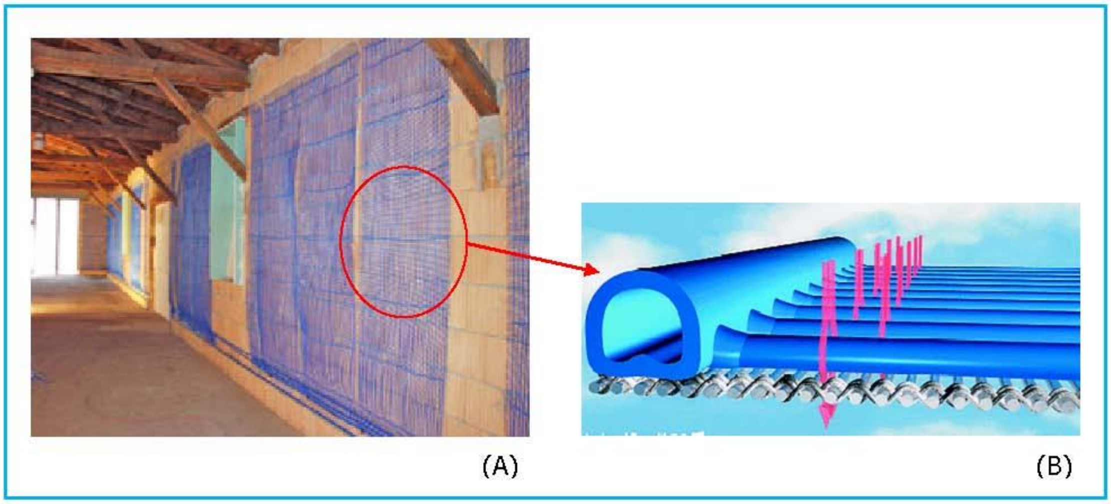


Figure 1.3. Capillary tubes (A) Capillary tubes for radiant cooling (B)
Source: (KaRo Systems 2007)

1.2.3.1.1 RC ceiling systems

For RC systems in the ceiling, there are typically three different names used:

a) Radiant ceiling panels or radiant cooling ceiling panels.
b) Chilled ceiling panels.
c) Chilled beams.

For all RC ceiling systems, the common criterion is: their cooling effects influence the space(s) underneath, mainly through radiant heat exchange, (see Figure 1.1 and Figure 1.4). However, in some cases the air surrounding the cooled surface -above and/or under- cools by conduction and then air falls into the space due to convection or buoyancy forces.

Radiant cooling ceiling panel system *(RCCP)*: the pipes carrying the chilled water are embedded in panels made out of different materials, such as aluminum or gypsum board. The primary heat exchange happens through radiation with a small percentage through convection. The system does not have air distribution parts or components as shown in Figure 1.4.

Figure 1.4. Suspended (or Free hanging) metal RC panels
Source: (Jeong and Mumma 2007)

Chilled ceiling panels and chilled beams: these two terms most often refer to those systems where forced air is part of the system, high-velocity nozzle type diffusers directing airflow along panel surfaces. However, some researchers and manufacturers are using this name for radiant cooling ceiling panels as previously introduced. In other cases they add the prefix "active" to clarify that forced air is part of the system and the prefix "passive" when forced air is not involved. Figure 1.5 shows a chilled beams system (chilled ceiling panels/ active radiant cooling system).

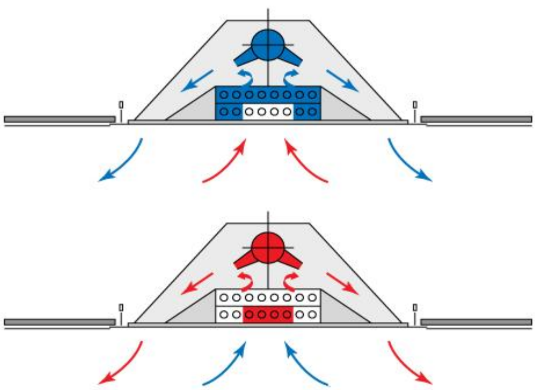


Figure 1.5. Active chilled beams (Active radiant cooling system)
Source: (SmithGroup 2008)

For this research, the *radiant ceiling cooling panel* system (RCCP) (shorten as *ceiling panels*) definition is used when forced air is not part of the system and the *active chilled ceiling system* definition is used when forced air is part of the system.

1.2.3.1.2 Slab systems

For slab systems there are four main configurations:

a) Pipes are in the middle of the slab.
b) Pipes are in the lower part of the slab.
c) Pipes are in the upper part of the slab.
d) Air-radiant floor system.

For these systems the water circulation pipes are embedded in the concrete slab to take advantage of the thermal capacity of the concrete. Through the circulation of the chilled water the slab is cooled and absorbs heat from the space. The position of pipes within the slab and the slab configuration determine the slab cooling behavior. The three configurations include:

a) The pipes are installed in the middle of the slab and there is no insulation layer within the slab. For this system the upper and the lower surfaces become the cooled surfaces and the slab will absorb heat from the upper and lower spaces respectively as shown in Figure 1.6. It is important to notice that the amount of heat flow to each side depends on the heat exchange coefficient between the surface and the room, where the angle/view factor between the heat source and the chilled slab is an important factor. This relationship is explained in the section of mean radiant temperature calculation 3.1.2.3.7.

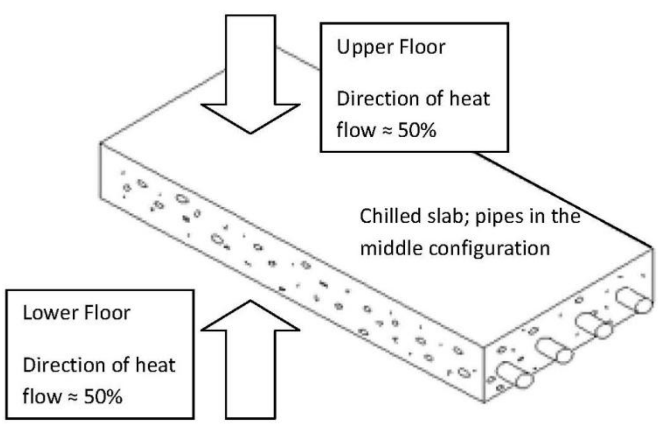


Figure 1.6. Chilled slab; pipes in the middle configuration

European literature most often refers to this configuration as a *Concrete Core Temperature Control System (CCTCS)*. However, the same name may refer to the situation where warm or cooled ***air*** is circulated through holes in the slab utilizing the concrete thermal capacitance.

The pipes are installed in the lower part of the slab and there is an insulation layer above. In this case, most of the radiant heat exchange occurs through the lower surface of the slab (ceiling side). This configuration is most common on the building's upper floor, Figure 1.7.

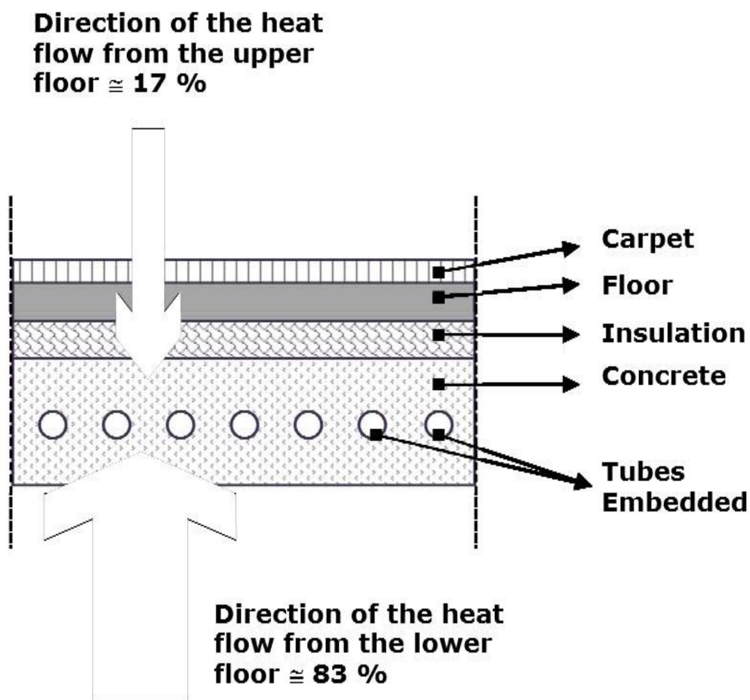


Figure 1.7. Chilled slab with thermally active ceilings
Source: (Center for Building Science News, 1994)

The pipes are installed in the upper part of the slab and there is an insulation layer underneath. In this case most of the radiant heat exchange occurs through the upper surface of the slab. This configuration is most common on the building's ground floor, Figure 1.8.

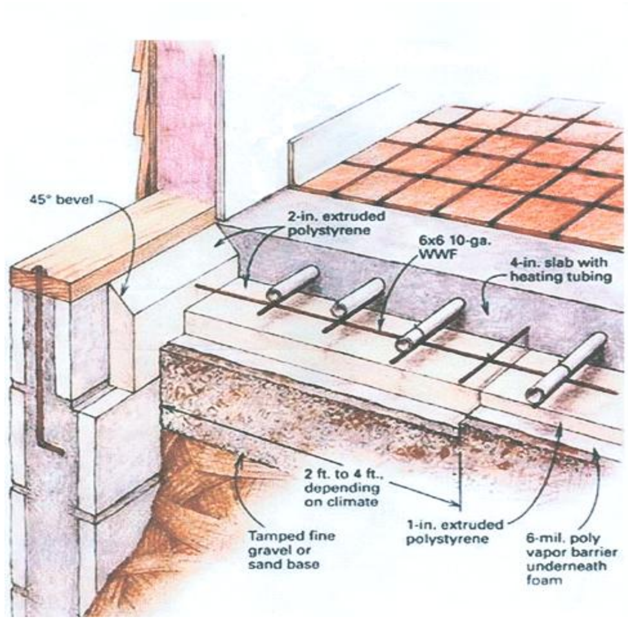


Figure 1.8. On-grade chilled slab
Source: (Radiant Floor Company, 2009)

In this research, the term *chilled slab* is used with an indication of an actively cooled surface in each case.

b) Air-radiant floor system, where cooled air is circulated underneath the floor before being released at the perimeter for space ventilation. The cooled floor will absorb heat, mainly through radiation, from the space, and loses it to the cooler air circulating in the slab. Hot air could be used during the winter, Figure 1.9.

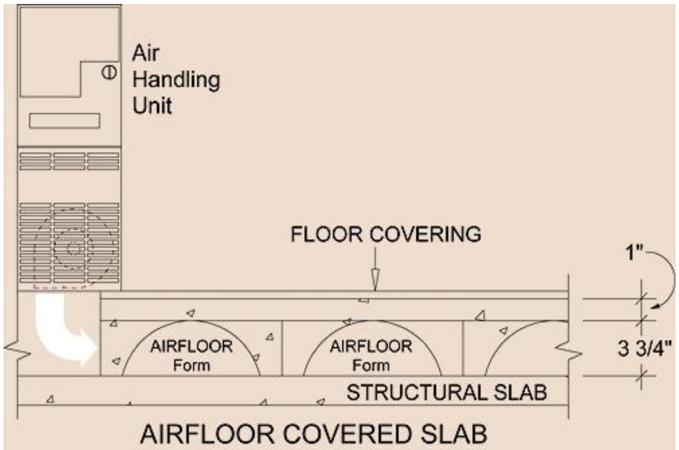


Figure 1.9. Air-radiant floor system
Source: (Airfloor 2009)

Table 1.1 summarizes RC systems names and types discussed previously

Table 1.1. RC systems: names and types

RC cooling system types according to their location		Description	Name used in this research	Discussed in this research
In the ceiling	Radiant Cooling Ceiling Panels System (RCCP) Or Radiant Ceiling Panels System	The pipes carrying the chilled water are embedded in panels suspended or mounted in the ceiling. The primary heat exchange happens through radiation with a small percentage through convection. The system does not have air distribution parts or components.	Radiant Cooling Ceiling Panel (Ceiling Panels) (RCCP)	Yes
In the ceiling	Chilled Ceiling Panels System Or Chilled Beams System Or Active Radiant Cooling System	The pipes carrying the chilled water are embedded in panels suspended or mounted in the ceiling. Forced air is part of the system (high-velocity nozzle type diffusers directing airflow along panel surfaces)	Chilled Beams	No
In the Slab	Pipes are in the middle of the slab Or Concrete Core Temperature Control System (CCTCS)	The pipes are installed in the middle of the slab and there is no insulation layer within the slab. The upper and the lower surfaces become the cooled surfaces and the slab will absorb heat from the upper and lower spaces respectively	Chilled slab with both sides active	Yes
In the Slab	Pipes are in the lower part of the slab	The pipes are installed in the lower part of the slab and there is an insulation layer above. Most of the radiation heat exchange occurs through the lower surface of the slab (ceiling side).	Chilled slab with active ceiling	Yes
In the Slab	Pipes are in the upper part of the slab	The pipes are installed in the upper part of the slab and there is an insulation layer underneath. Most of the radiation heat exchange occurs through the upper surface of the slab.	Chilled slab with active floor (Chilled floor)	Yes
In the Slab	Air-radiant floor system	Cooled air is circulated underneath the floor before being released at the perimeter for space ventilation. The cooled floor will absorb heat, mainly through radiation, from the space, and loses it to the cooler air circulating in the slab.	Air-radiant floor system	No
In the wall		The pipes carrying the chilled water are attached or embedded in the walls, covered with plaster, or exposed to the interior space	Radiant wall system	No

1.2.4 RC system components

When considering a RC system, the architect and the HVAC engineer need to work together for better and successful results. However, the architect is mainly concerned with four major components: the cooled surfaces of the system, the source and distribution of the cooled water, the ventilation system associated with the RC system, and the dehumidification system associated with the RC system. The first two components are essential components of the RC system; the cooled surface is where the heat exchange occurs and the cooled water is necessary to carry the heat away and to keep the cooled surface temperature low, as desired. However, introducing a RC system as an alternative to conventional HVAC systems requires the designer to identify the ventilation system/strategy, which will also satisfy the latent heat loads, and the dehumidification system, which will maintain the relative humidity above the dew point of the RC systems cooled surfaces.

1.2.4.1 The cooled surface

As explained in the previous section 1.2.3.

1.2.4.2 Cooled (chilled) water

There are many ways to produce the chilled water circulated in a RC system. Chilled water can be produced by:

a) Conventional water chiller; there are many configurations of water chillers.
b) Cooling tower.
c) From geothermal –ground or water- loop.

One of the advantages of RC systems is that they run with relatively high temperatures. While conventional HVAC systems use 42 ˚F - 44 ˚F chilled water to operate, the minimum surface temperature to operate a chilled slab system is 67 °F (Simmonds, Mehlomakulu, and Ebert 2006) (sections 3.1.1.1.2 and 4.5.2 discuss this point in more details). This advantage allows the system to use cooled water coming directly from non-intensive/ low-exergy energy sources such as a geothermal heat pump (ground loop). At the same time, RC system effectiveness is correlated with its large radiative exchange area relatively to a conventional HVAC system.

In a study of a house located in Montreal conducted by Zmeureanu and Brau (2007), they concluded that when using an underground heat exchanger coupled with radiant cooling floor, it is possible to keep the summertime operative temperature within thermal comfort conditions without using energy for mechanical cooling (to cool down the circulated water).

1.2.4.3 Ventilation strategies

Traditionally, conventional HVAC systems provide a sufficient amount of fresh air to conditioned spaces and remove the contaminants to maintain acceptable Indoor Air Quality (IAQ). Also, HVAC systems provide the air with appropriate temperature to remove the heat from the conditioned spaces and maintain acceptable thermal comfort environments.

RC systems have the ability to remove the heat directly by radiation and indirectly by convection. RC systems do not provide air for ventilation neither do they satisfy the latent cooling loads. According to ANSI/ASHRAE 62.1 (2007), spaces intended for human occupancy have to be ventilated naturally or mechanically to provide acceptable indoor air quality. This means RC systems must be supplemented with a ventilation air system/strategy. In general there are four modes of delivering and exhausting air to/from the space:

a) Through a mechanical ventilation system (duct system) using conventional HVAC systems such as constant air volume or variable air volume (VAV), or by using Dedicated Outdoor Air Systems (DOAS).
b) Through a natural ventilation strategy, when outdoors conditions allow.
c) Hybrid ventilation mode, by designing the space to have the previous two modes.
d) Infiltration, through the unintentional entrance of the outside air into the buildings, which is typically used in residential buildings.

Separating the cooling system (RC systems) from the ventilation system may have the following benefits:

a) Based on a study of office buildings with conventional HVAC systems, Stetiu (1998) mentioned that "at the time of peak cooling load, only 10%-20% of the supply air is fresh air, and only this small fraction of the supply air is necessary to ventilate buildings to maintain acceptable indoor air quality".

b) For spaces with RC systems and dedicated ventilation systems, the duct cross-sectional dimensions become much smaller than those used in forced-air systems which make the vertical plenum space savings possible, and smaller vertical shafts (Conroy and Mumma 2001).
c) Supply and return fan size are also significantly reduced (Conroy and Mumma 2001).

Combining the RC system with different the ventilation strategy/systems have different consequences and consideration the designer should understand. These different combinations are discussed in section 3.1.2.5.1.

1.2.4.4 Dehumidifiers

Due to the fact the RC systems can remove directly the sensible heat from the conditioned spaces and indirectly some of the latent heat by convection. In spaces with latent cooling loads it is necessary to consider a dehumidification system, if the combined ventilation strategy/system does not control the indoor RH. The dehumidification system is a) to maintain the indoor RH within the comfort limits of the occupants as explained in section 3.1.2.3.9, and b) to maintain the indoor dew point temperature to be above the surface temperature of the cooled surfaces and thus avoid possible condensation situation.

When dealing with ambient humidity control, there are two approaches:

a) Cooling the air to condense the water vapor; or
b) Passing the air over a desiccant material to pull moisture from the air, and then regenerating the desiccant by some heat source.

1.2.4.4.1 Cooling-based dehumidification

As the name indicates, with cooling-based dehumidification the air is cooled to its dew-point, which then causes the moisture to condense on the cooled surfaces, Figure 1.10. Cooling the air further will condense more moisture from the air. Care must be taken to not lower the moisture content too much as dry room air conditions could result.

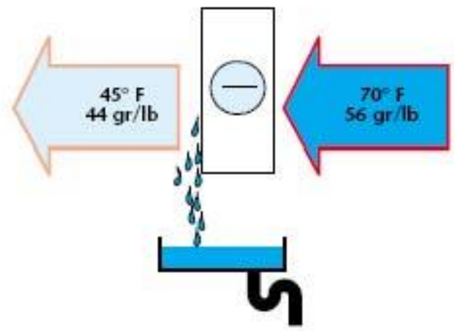


Figure 1.10. Schematic drawing for cooling-base dehumidifier
Source: (Harriman 2002)

1.2.4.4.2 Desiccant-based dehumidification

With desiccant-based dehumidification, instead of cooling the air to condense moisture, “desiccants are used to attract moisture from the air by creating an area of low vapor pressure at the surface of the desiccant. The pressure exerted by the water in the air is higher, so the water molecules move from the air to the desiccant and the air is dehumidified” (Harriman 2002).

Figure 1.11 explains the air dehumidification process using a desiccant material. When the desiccant material, liquid or solid, is cool and dry (point 1), it attracts moisture from the air as its surface vapor pressure is lower than the surrounding air. As the desiccant material collects vapor from the surrounding air, it becomes wet and warm with a vapor pressure at the surface equal to the surrounding air, making it unable to collect more moisture from the air (point 2). To move the moisture out of the desiccant material, the desiccant material is taken away from the moist air, heated, and then placed into a different airstream. Heating the desiccant material will make its surface vapor pressure very high; this will make the moisture to move out to the surrounding air trying to reach the equilibrium status (point 3). At this point, the desiccant material is dry and hot and it cannot attract moisture, as its surface vapor pressure is very high. When the desiccant material is cooled, its surface vapor pressure will be very low, and the cycle begins again (point 3 to 1).

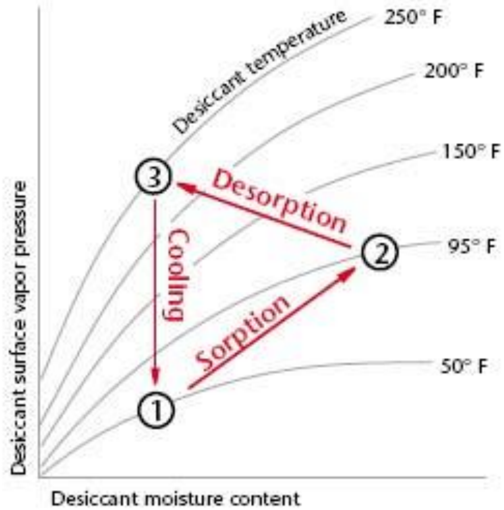


Figure 1.11. Air dehumidification process using a desiccant material
Source: (Harriman 2002)

Figure 1.12 explains the process of desiccant dehumidification on the psychometric chart. In this process, when the moisture leaves the processed air it releases its heat to both the air and the desiccant material. The amount of the released heat is proportional to the amount of moisture extracted from the air.

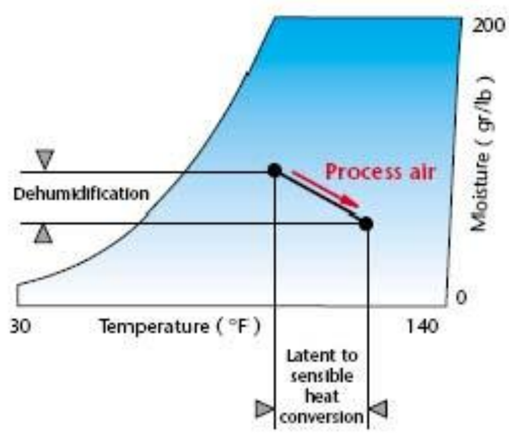


Figure 1.12. Air dehumidification process using desiccant material in the psychometric chart
Source: (Harriman 2002)

Harriman (2002) explained the efficiency of this strategy saying; "the efficiency of the process improves when the desiccant has a high moisture capacity and a low mass. The ideal desiccant dehumidifier would have an infinitely high surface area for collecting moisture, and an infinitely low mass, since the required heating and cooling energy is directly proportional to the mass of the desiccant and the mass of the machinery which presents the desiccant to the airstream."

When comparing cooling-based and desiccant-based dehumidifiers, one can notice, as shown in Figure 1.13, that cooling-based dehumidifiers are generally more available in smaller sizes. Desiccant-base dehumidifiers are common for large airflows. Among cooling-based dehumidifiers, the DX, pre-packaged units are generally more available in smaller sizes, while the chilled liquid types are more common when very large airflows are to be dehumidified. Among the desiccant-based types, the liquid spray type is commonly used in larger sizes, and solid packed-tower for smaller applications. For larger airflows than shown here, most manufacturers build up the system using smaller units as modular components.

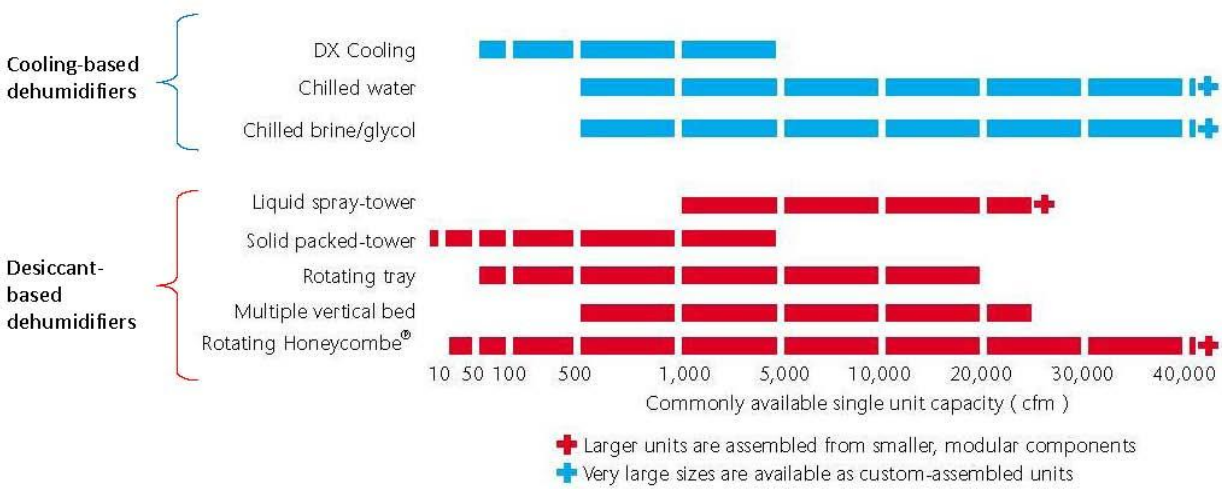


Figure 1.13. Dehumidification strategies and their common available capacity
Source: adapted from (Harriman 2002)[1]

Figure 1.14 shows the relationship between the dehumidifier strategy and the air dew-point that can be delivered continuously. As shown, cooling-based dehumidifiers cannot deliver air with a dew point less than 32 ˚F, where desiccant-based systems can deliver air with extremely low dew point temperatures.

[1] Rotating Honeycombe mentioned in Figure 1.13 and Figure 1.14 are products of Munters Corporation.

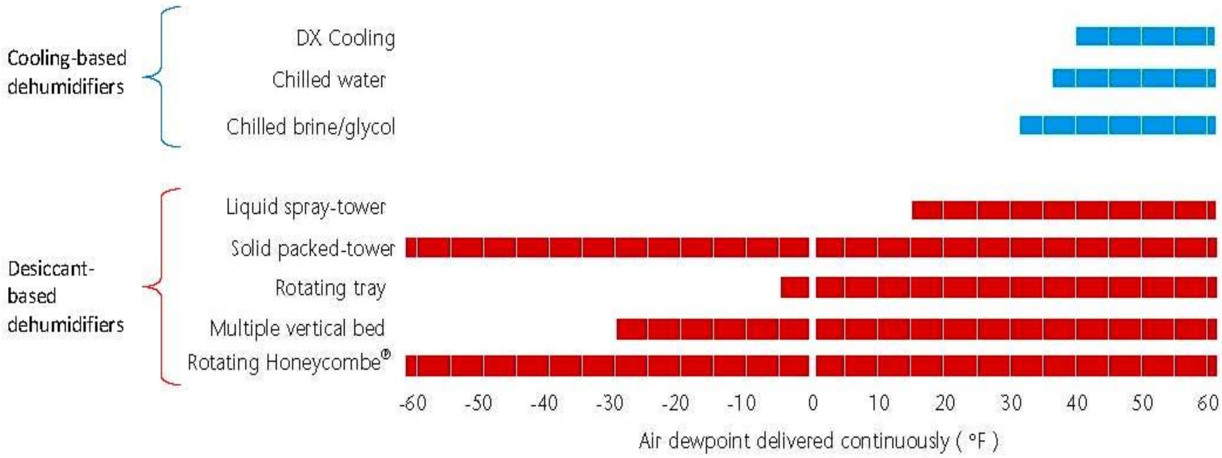


Figure 1.14. Dehumidification strategies and the airflow dew-points they can deliver
Source: adapted from (Harriman 2002)

Harriman (2002) claimed that “cooling and desiccant-based dehumidification systems are most economical when used together. The technologies complement each other; each strength of desiccants covers a weakness of the cooling systems and vice-versa.” In addition, cooling-based dehumidification systems are more economical than desiccants at high air temperatures and moisture levels. However, they are rarely used to dry air below a 40 °F dew point because condensate freezes on the coil, reducing moisture removal capacity. Desiccants are very efficient when drying air to create low relative humidity, and cooling-based dehumidification is very efficient when drying air to saturated air conditions. Desiccant dehumidifier are wildly used in supermarkets, hotels, restaurants, and office buildings specially in hot humid climates (Pesaran 1994).

1.3 The Need for This Research

1.3.1 Global warming and space conditioning

1.3.1.1 Definition and causes

Solomon et al. (2007) stated in the *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basic* that: “Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation, and in land surface properties alter the energy balance of the climate system. Global warming, which is a specific example of global climate change, could be understood as the increase of the global average air and ocean temperatures that cause snow and ice melting and rising of the sea level (Solomon et al. 2007).

Slowing or reversing global warming has become an important goal for many countries and professions during the past decade. Much recent evidence suggests, human activities have been increasing the concentration of greenhouse gases (carbon dioxide, water vapor, methane, nitrous oxide, ozone and chlorofluorocarbons (CFCs)) in the atmosphere for the past several decades (Solomon et al. 2007). These gases are produced by many processes including product manufacturing, transportation and operation of buildings. These gases absorb the longwave energy re-radiated from the Earth's surface which causes the atmosphere to warm. One of the main sources of greenhouse gases is the combustion of fossil fuels (coal, oil and natural gases) to produce usable forms of energy.

1.3.1.2 Energy consumption in the U.S.

According to the U.S. Department of Energy (DOE) (2009), the United States used 101.5 quadrillion British thermal units (Btus) (105 exajoules, or 29000 Trillion Watt hours (TWh)) of energy in 2008. The major source of this energy was fossil fuels. This included 37% from petroleum, 23.2% from natural gas, 22.3% from coal, 8.2% from nuclear electric power with the remaining 6.6% coming from renewable energy sources, Figure 1.15.

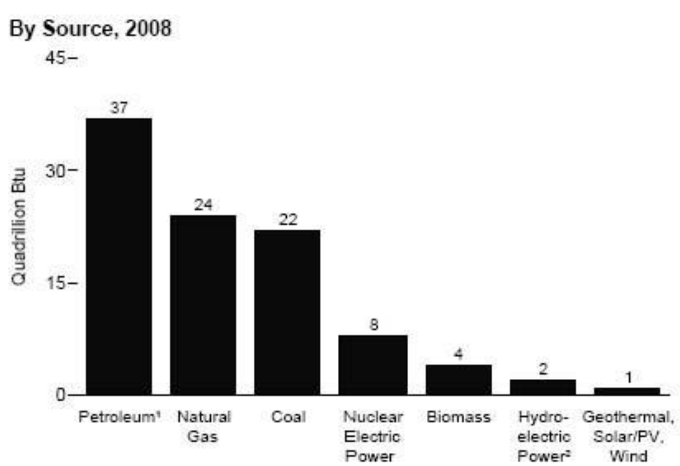


Figure 1.15. U.S. Energy consumption by source in 2008
Source: (U.S. Department of Energy 2009)

1.3.1.3 Energy consumption by sector

Figure 1.16 from the U.S. Department of Energy (2009) shows the energy consumption from the four main consumption sectors during 2008. It can be noticed that the industrial sector consumed the largest amount at (31%) of the total consumption, followed by the transportation sector (28%), then the residential sector (22%) and finally the commercial sector (19%).

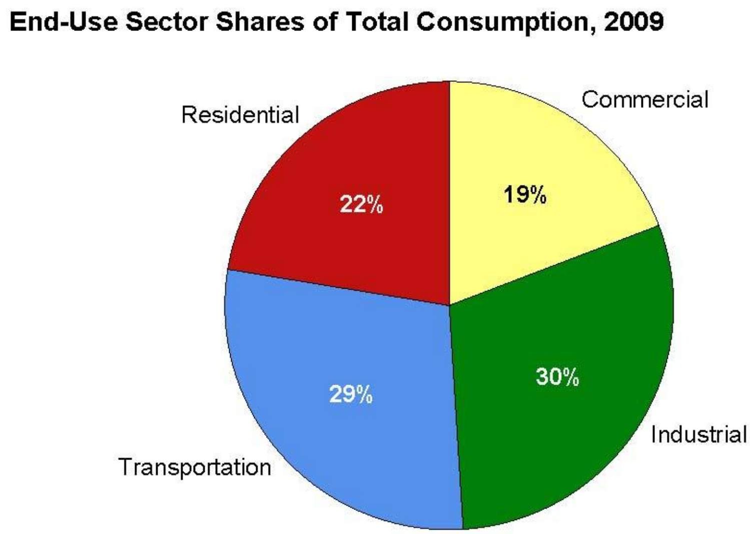


Figure 1.16. U.S. end-use energy consumption by sector in 2008
Source: (Energy Information Administration 2010)

1.3.1.4 Energy consumption by system

According to the U.S. Energy Information Administration (2010) the total consumption by energy end uses in 2005 in the residential sector was about 10.55 quadrillion Btus; about 8.3% was for cooling purposes and 40% for heating purposes. In 2003 and as shown in Figure 1.17, the total fuel consumption by end use, in the U.S. commercial sector, was about 6.5 quadrillion Btus, about 7.9% was for space cooling purposes, 6.6% was for ventilation purposes, and 36% was for space heating (Energy Information Administration 2010).

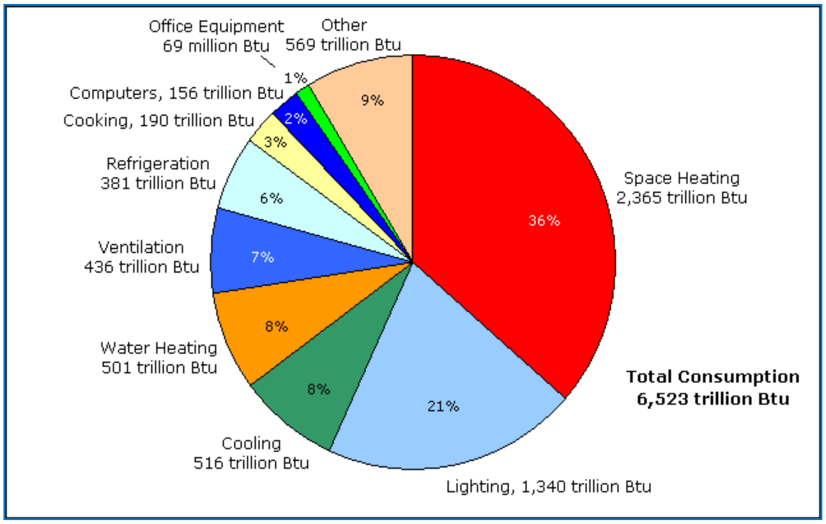


Figure 1.17. U.S. commercial buildings energy consumption in 2003
Source: (Energy Information Administration 2010)

Table 1.2 shows the breakdown of the commercial and residential sectors into major use categories.

Table 1.2. Energy Consumption in the United States by the end-use in the commercial and residential sectors
Source: Adapted from (Energy Information Administration 2010)

Energy End Uses (Quadrillion BTUs)		Space Cooling	Space heating	Ventilation	Water heating	Refrigeration	Lighting	Cooking	Office equipments	Computers	Others	Total
Commercial Sector	Year 2003	0.516 (7.9%)	2.365 (36.4%)	0.436 (6.7%)	0.501 (7.7%)	0.381 (5.8%)	1.34 (20.5%)	0.19 (2.9%)	0.069 (1%)	0.156 (2.4%)	0.569 (8.7%)	6.523 (100%)
Residential Sector	Year 2005	0.88 (8.4%)	4.3 (40.8%)	--	2.11 (20%)	0.51 (4.8%)	Plus other Appliances 2.74 (26%)	--	--	--	--	10.55 (100%)

1.3.1.5 The relevance to HVAC system selection and design

The reliance on energy-intensive active heating and cooling systems has many serious consequences. Stetiu (1998) suggested in her doctoral dissertation that some of the most consequential issues for HVAC system design and application include:

a) "Building professionals have lost much of their ability to design climate-responsive buildings".
b) "Many different parties are involved in the building process".
c) "Worker surveys reveal that commercial building occupants are increasingly dissatisfied with the thermal conditions of their workplace".
d) "Dramatic increases in the electrical power demand in the United States" and in the world as well, are not being addressed.
e) We are experiencing an "increasing emission of chlorofluorocarbon (CFC) and CO2 which are environmentally costly". However, according to Earth System Research Laboratory the current trend of CFC-11 and CFC-12 shows a decrease in these gases concentration after 2000 (Earth System Research Laboratory 2010)[1].
f) "People in developing hot countries are becoming less tolerant to their climate than they used to be".

In addition, architects must acknowledge and integrate HVAC systems early in the design process, as they affect many other architectural and non-architectural decisions.

These and other issues suggest building professionals, including architects and HVAC engineers, need to return to more climate-responsive design strategies and the use of more energy efficient heating and cooling technologies. According to the U.S. Office of Technology Assessment (OTA), "the use of cost-effective, commercially available technologies in the US could reduce total building energy use by about one-third by 2015" (Stetiu 1998).

Stetiu (1998) also mentioned, based on OTA recommendations in 1992, "alternative cooling technologies can reduce the energy consumption and peak power demand due to space conditioning while striving to provide indoor conditions very similar to those provided by the compressor-driven technology… [And that can save] up to 28% of the U.S. energy consumption

[1] On September 21, 2007, about 200 countries agreed to accelerate the elimination of hydro-chlorofluorocarbons entirely by 2020 in a United Nations-sponsored Montreal summit.

due to space conditioning [energy consumption by cooling equipment]". Even though the cold water in the RC system may still provided by a refrigeration process, part of the energy saving comes from the fact that water in RC systems needs to be cool to around 67 °F instead of 42 °F - 44 °F as in conventional HVAC systems as explained in section 3.1.3.1.

One of the most promising HVAC technologies is RC. This technology is widely used in Europe but rarely found in the U.S. and that, according to Stetiu (1998), is due to a "complex interaction of technical, economic, social, and cultural factors". The climate factor in the U.S. could be added as another important barrier. Many of these factors are addressed through this work.

1.3.1.6 Exergy in the built environment

The growing interest in green building design has led to the use of the concept of exergy in built environments. Kanoglu, Dincer, and Cengel (2009) defined exergy as: "The useful work potential of a given amount of energy at a specified state … It is also called the availability or available energy". According to Kilkis (2005) and Dietrich (2009), the low-exergy systems approach is a main objective to a sustainable built environment. A reason for this interest is to focus more beyond the end-user measures such as better insulation, efficient light bulbs, reducing electricity demands, etc.

This energy may be from either renewable or non-renewable sources, or it may be captured from waste processes. Therefore to produce energy efficient buildings, which use natural resources wisely and exergy consciously, it is required to tie natural low-exergy energy sources such as solar, wind, geothermal, and waste heat with low-exergy building systems such as the RC system.

RC systems are considered to be low-exergy building systems due to the fact that they normally operate with a low temperature profile, meaning a moderate supply water temperature both in cooling and heating modes, relatively to conventional HVAC systems.

1.3.2 Comfortable Indoor Environment (IE)

While most people spend about 90% of their life in indoor environments, many factors related to this environment such as exposure to nature and daylight, air quality, temperature, odors, noise, ergonomics, and opportunities for social gathering, relaxation, and exercise, affect people's performance and well-being.

When studying the relationship between the indoor environment quality (IEQ) and occupants' health -which is directly related to occupants' performance and productivity- it is noted that a great deal of researchers have focused on building-related illnesses. Heerwagen and Judith (2000) said:

> *Much less attention has been given to the environment as a health promoting factor. That is, does the absence of symptoms by itself mean that one is in a state of well-being? Or is the sense of well-being associated with the presence of particular features and attributes, rather than just the absence of harmful ones? Although there is not as much research on this topic, it appears that illness and well-being are influenced by different building features and conditions. Thus, just getting rid of building problems may be necessary, but not sufficient, to promote highly positive states of well being (p.9).*

Proof by contradiction is a useful concept, mainly in applied sciences such as mathematics and engineering, and one may argue it could be used in other disciplines. This concept could be applied to the built environment, that is, if the built environment does not cause harm to its occupants in any form, then it could be assumed it provides for well being, otherwise what are the benefits of its construction?

Although there is not complete agreement on the factors which define a comfortable indoor environment, it could be suggested that those factors which are related to human physical sensations are common to all definitions. Those main factors are: thermal, acoustic, visual, and indoor air quality. Other factors such as safety, aesthetic values, etc. are no less important, but they are more difficult to quantify and even more difficult to measure and assess.

A building is mainly constructed to protect its users and occupants from the external environmental conditions while providing a healthy and comfortable environment. Creating a comfortable indoor environment means to approximate people's sensory conditions with which they are most comfortable and at ease (Flynn et al. 1992). For example, when considering institutional and office buildings, providing a comfortable indoor environment to increase productivity becomes a main goal.

However, the Whole Building Design Guide (WCDG) (2008) argues that “it is often hard to quantify the impacts of specific components of the indoor environment on productivity, because individual and group work effectiveness is tied to many different factors—including compensation levels, management practices, and environmental comfort. It is difficult, if not impossible, to isolate individual physical factors, such as the presence or absence of team rooms, daylighting, natural meeting places, or control over the environment. This problem is exacerbated in the case of white-collar workers whose ‘output’ [author emphasis] is knowledge or insight that cannot be easily quantified”.

Many studies reported and showed that the use of RC systems in a space will improve its interior environment related to human sensation as mentioned previously. In a study done by Imanari, Omori, and Bogaki (1999) comparing the thermal comfort sensation from a conventional air-conditioning system with RCCP system they found that both female and male subjects favored radiant ceiling cooling panels as the system was capable of creating smaller variation of air temperature and eliminated the undesired drafts caused by conventional air-conditioning systems.

With the implementation of RC systems, there is an opportunity to improve IAQ. Radiant cooling systems do not deliver air for ventilation nor do they take care of the latent cooling loads in the conditioned space. However, when coupling RC with a Dedicated Outdoor Air System (DOAS) there is a good chance to improve IAQ since a DOAS brings 100% outdoor air to the conditioned space and does not recirculate air from the space (Mumma 2001). Moreover, there is a possibility to implement RC systems in naturally ventilated buildings if the climate permits; if the outside temperature is lower than the inside temperature and the dew point of the outside air is higher than the inside air. This situation cannot be achieved when using conventional HVAC systems.

From an acoustical point of view, one of the problems associated with conventional air-conditioning systems is noise. HVAC noise affects not only building occupants, but it has its influence in the surrounding environment, especially if rooftop units are in use. Noise sources in traditional HVAC systems are many; chillers, boilers, and air handlers. In most cases noise is transmitted to the indoor environment in the process of delivering the conditioned air. However, when using RC systems, the amount of the delivered air is typically much smaller than all-air systems, as the airflow for RC systems is just to satisfy the ventilation requirement and to take care of the latent heat removal, which is often about 20% of the normal all-air conventional system (Conroy and Mumma 2001). This means, smaller ducts and less flow which leads to lower transmitted noise to the room and lower generated noise in the system.

The implementation of RC could improve the visual environment of the space. With the use of RC systems, the ceiling height could be raised as the plenum space needed for radiant ceiling cooling panels and its ventilation system is much less than what is needed in conventional HVAC systems. In the case of the chilled slab, ducts are only needed to supply air for ventilation purposes and take care of the latent heat load as mentioned above (Conroy and Mumma 2001). This means the ceiling could be raised, or a new floor could be added every five floors or so when compared to traditional buildings with all-air conditioning systems (Conroy and Mumma 2001).

1.3.3 Bridging the gap

In practice, there is a gap between architecture and other disciplines involved in the construction industry. This gap, which may be considered to be a relatively recent development, is due to the division in the responsibilities, the division in the educational systems, and the complexity of today's buildings (Faridah, Sani, and Ismail 2004). Faridah, Sani, and Ismail (2004) stated that architects and engineers are encouraged to understand the work of each other as there is a direct need to bridge the gap between them. This understanding could lead to better built environments.

Moore, Bauman, and Huizenga (2006) and Stetiu (1998) argued that one of the limitations of using and implementing RC systems in North America is due to the lack of familiarity with such cooling strategies by designers. This lack of familiarity may refer to the previous reason of division in responsibilities and moreover to the division in the educational systems for engineers and architects. To bridge the gap between architects and engineers Faridah, Sani, and Ismail (2004) suggested that we need an architect with the ability to implement engineering knowledge in architectural design and the need for an engineer with understanding and appreciation for architectural and aesthetic issues.

For designers and architects, understanding the consequences of using any system in their building is required. All systems should not be taken as a black box. Understanding the system whether RC or conventional will help improve the final performance of the space.

This research is a step toward the bigger goal of bridging the gap between architects and other disciplines. The RC system is a cooling system with potential advantages over other HVAC systems. However, RC systems require collaboration between architects and engineers early in the design process. This research focuses mainly on what architects and HVAC engineers should know and understand about RC systems. It is hypothesized that through this understanding RC systems will be more frequently used in buildings.

1.4 Problem Statement

The implementation and use of RC systems in buildings may help reduce total energy consumption and may provide an enhanced, thermally comfortable indoor environment under certain circumstances when compared to conventional HVAC systems. Energy consumption reductions are due to the lower energy input needed by RC systems to provide the same amount of cooling as compared to conventional HVAC systems. For thermal comfort, studies show that exchanging heat through radiation makes the human body feel more thermally comfortable than exchanging heat through convection (Imanari, Omori, and Bogaki 1999; Dagostino and Wujek 2004). For these and other reasons the use of RC systems in buildings is increasing worldwide.

To be most cost beneficial, RC systems should be considered and integrated during the early stages of design. Moreover, issues associated with these systems must be understood and properly applied by architects as well as HVAC system designers. The barriers and constraints associated with RC systems must also be understood and considered as part of the design decision-making process. With this, it becomes clear that the proper design and implementation of RC systems can be complex, which may be one reason for slow acceptance of this technology in the U.S. Therefore, a primary goal of this research is to capture the knowledge related to the design and implementation of RC systems and map this knowledge to a decision-support structure.

The purpose of this study is to identify the relevant performance mandates, design issues, barriers and constraints, and potential advantages for the implementation of RC systems especially in the U.S. These will then be mapped to a decision-support structure for architectural design. Including these points in this decision-support framework, a systematic way will be available for architects and HVAC designers who are considering the use of RC systems in their designs. Performance assessment procedures will be proposed and mapped as shown schematically in Figure 1.18.

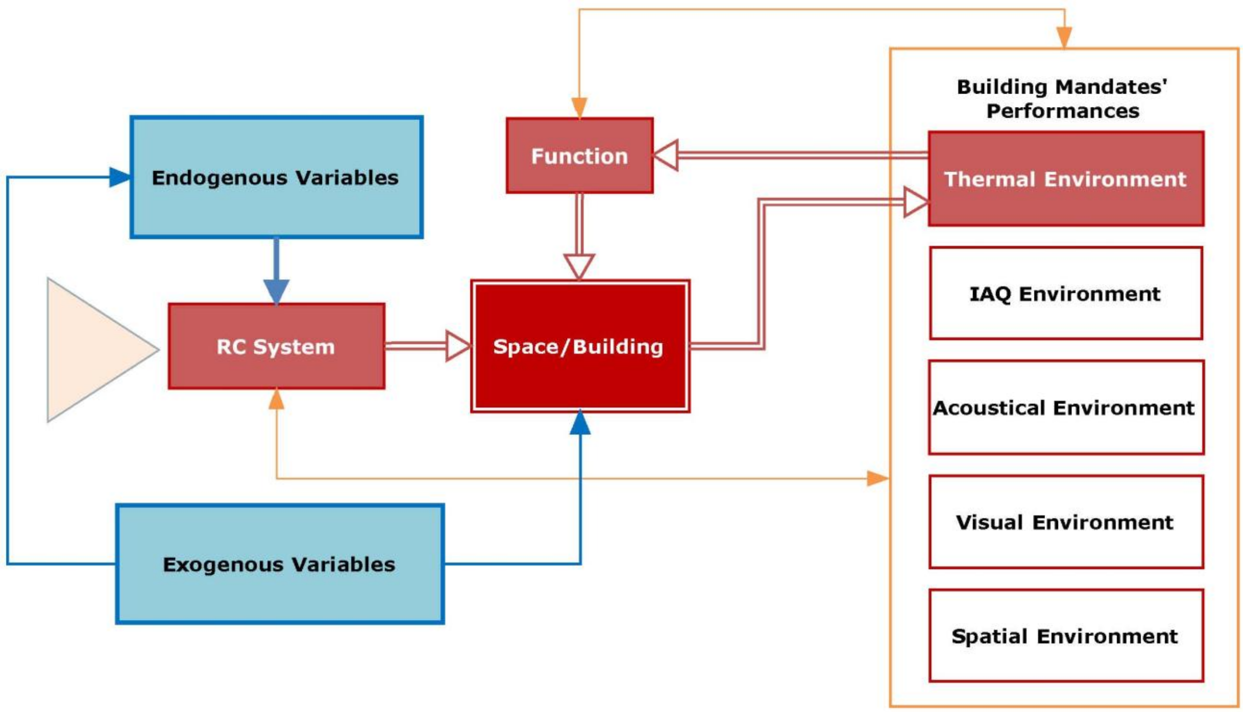


Figure 1.18. Schematic representation of the RC system decision-support framework

Figure 1.18 represents an overview of the RC system decision-support framework this research will develop. The research problem may be summarized as follows: the main purpose of installing the RC system in a space/building is to enhance the thermal comfort environment, which is an important building performance mandate, so the space/building will be utilized and occupied beneficially according to its proposed function(s), see red squares. However, as with any mechanical system, there are endogenous variables (variables proceeding from within the system, see light blue box) and exogenous variables (variables originating from outside the system, see dark blue box) to be analyzed and well understood by the architect and the HVAC system designer in order to make the installation of the RC system successful.

These endogenous and exogenous variables may form constraints and limitations for the use and implementation of a RC system. Also, in most buildings, RC systems are not the only system installed; other systems such as lighting, plumbing, ventilation, etc. are installed to meet specific building performance mandates or to work with the RC system. Designers must integrate these systems carefully. The integration of the RC system with these other building systems might pose constraints for the RC system. For example, the operation of the ventilation system may be constrained by the concern for humidity control and condensation on the cool surface of the RC system.

The installation of RC systems may impact compliance with the other building performance mandates and thus affecting the space function, see orange arrows. For this designers must think of system integration in early stages of design for better performance and to avoid failure.

Through a systematic literature review, case studies, and interviews with practicing architects and HVAC system engineers, this research is proposing a decision-support framework to assist architects and HVAC system engineers in the design and integration of RC systems in the early stages of design.

Through this decision-support framework, procedures are proposed and developed to quantitatively evaluate the relevant performance mandates; thermal performance, air quality, spatial performance, acoustical performance, and visual performance, by which the decision-maker will know whether the system is applicable for a certain space or not in any given project/building type. The decision-support framework will also provide notice when certain barriers or constraints are identified as serious obstacles to application for a given design scenario.

Cost and energy are important factors in any system implementation decision. Nevertheless these two factors will not be included in detail in the proposed decision-support framework; section 3.1.3 discusses these two factors briefly and separately.

In future, this decision-support process may be mapped and translated to a graphic format using decision-support software. This translation could eventually be integrated into a digital design domain combining Computer-Aided Design (CAD) and Building Information Modeling (BIM). This would result in a useful design tool for RC systems.

1.5 Research Goals and Objectives

The goals and the objectives of the research may be summarized as follow:

1.5.1 Goals

a) To reduce the impact of green house gas emissions and global warming by promoting low-exergy building systems as an alternative cooling strategy.
b) To provide a decision-support framework that will be adaptable to CAD and BIM design assistance tools.
c) To encourage the application of RC systems through the implementation of these new tools.

1.5.2 Objectives

a) Through a systematic literature review, case studies, and interviews the relevant issues, barriers, constraints, and evaluation procedures relevant to the design and application of RC systems will be identified.
b) The relevant issues, barriers, constraints, and evaluation procedures will be mapped to a decision-support process for architects and HVAC systems engineers.
c) This decision-support framework will explore and explain the architectural consequences of the implementation of RC systems in any given space.
d) The outcome of this research, the decision-support framework, will be adapted to and graphically presented using decision support language.

1.6 Study Limitations

While the goal is to develop the decision-support framework for a wide range of building types, the framework may be limited by the case studies and interviews, as these data samples may not include all building characteristics.

This research studies two types of RC systems; chilled slab and radiant cooling ceiling panel systems as they are defined in section 1.2.3.

This research mainly studies the design and application of RC systems in new construction buildings, with less focus on retrofit projects.

The proposed decision-support framework does not directly include the cost and energy consumption of the RC system in detail. This is because a) the focus of this research is on decision-making in the early stages of the architectural design process; since cost assessment depends on specific system characteristics (piping sizes, length of tubing, etc.) that are not known during this phase of design, and b) it is not within the scope of this research. A detailed cost assessment for the use of RC systems is required in the future to develop the proposed framework.

1.7 System Implementation Constraints

As with any mechanical system, if the RC system does/will not perform as expected or/and desired, or if a conflict occurs with another building performance mandate, then the cause(s) of this problem or conflict become potential constraints to RC system implementation. Examples from around the world show that it is possible to install and operate a RC system under different situations. This makes understanding the system capabilities, limitations, and expected performance as important as identifying the causes, obstacles, and barriers for its installation.

On the other hand, when considering the reasons for the infrequent application of RC systems in the U.S., Moore, Bauman, and Huizenga (2006) mentioned: "education appears to play a particularly critical role where experience with radiant cooling is lacking or limited". Feustel (1999) explained that "fear of designing and building something unfamiliar and not having the right tools to size the systems properly" is a constraint.

This research does not deal with pre-defined constraints; instead it clarifies the system's capabilities, limitations, and expected performance in reference to specific features. It also tries to identify possible failure situations and the ways to overcome them.

2 FRAMEWORK METHODOLOGY

2.1 Introduction

The main goal of this research is to capture and structure knowledge, thus helping architects and designers make more informed decisions with regard to RC systems. For this, a grounded theory approach with systematic literature review, case studies, and interviews as tactics are used.

Some decisions in the architectural design process are subjective and cannot be governed by equations and codes. Those subjective issues could be referred to as the human factor. To acknowledge these issues, means sources other than literature, codes, standards, etc. are included while developing this framework. Case studies and open-end questionnaires (interview) helped to capture the subjectivity in the decision process when implementing RC systems.

2.2 Qualitative Research Method - Grounded Theory

Grounded theory is systematic inductive theory generation methodology, where the research theory emerges at the end. The emergence of the theory distinguishes the grounded theory approach from other research methods which test a hypothesis. However, Strauss, one of the founders of the grounded theory approach, argued that deduction and verification is needed in the grounded theory approach as much as induction (Groat and Wang 2002). In this research, the proposed decision-support framework for the design and application of RC systems is the emergent theory.

Groat and Wang (2002) mentioned Strauss and Corbin, 1998 definition for the grounded theory approach as :

> *In this method, data collection, analysis, and eventual theory stand in close relationship to one another. A researcher does not begin a project with a preconceived theory in mind (unless his or her purpose is to elaborate and extend existing theory). Rather, the researcher begins with an area of study and allows the theory to emerge from the data… Grounded theories, because they are drawn from data, are likely to*

offer insight, enhanced understanding, and provide a meaningful guide to action (p.181).

Under the grounded theory approach any data collection method could be used. Glaser and Strauss (2006) stated that different data sources or collection methods give the researcher different views or vantages: they called these different views “slices” of data. In this research data will be from literature review, case studies, and interviews of experts.

Based on the grounded theory approach as Groat and Wang (2002) described, there are three major stages: data collection, coding or data analysis, and memoing or theory building. Data sources are explained previously. In the coding stage, the research will categorize the collected data and identify sub-categories to draw the relationships between them. When the relationships between different categories are identified they are recorded in memos. Sorting the memos in a certain order will clarify the emerging theory or the framework.

Groat and Wang (2002) described an integrative research approach as “one whereby multiple methods from diverse traditions are incorporated in one study”. This is because each method of conducting research brings with it particular strengths and weaknesses. Combining methods provides appropriate checks against the weak points in each, while at the same time enabling the benefits to complement each other. Under this methodology Creswell (2003) defined three models: “the two phase approach, the dominant-less dominant design, and the mixed methodology design”. Out of these models the mixed methodology design seems to be ideal for this research.

Groat and Wang (2002) said:

The mixed-methodology design represents the most complete level of integration among two or more research designs. In this model, the researcher conducts aspects of both strategies in roughly comparable sequences, and with approximately equal degrees of emphasis. The advantage of such an approach is that the strength of each research design can complement each other, while the weaknesses of each design can be substantially offset (p368).

2.3 Systematic Literature Review

Traditionally, literature review aims to identify the current critical points of a certain topic. It provides a background of the findings, as well as theoretical, and methodological contributions to a particular topic, and help bringing the research question into focus. Literature review does not present new or original work as it mainly summarizes the research evidence and knowledge of the topic (Okoli and Schabram 2010).

However, systematic literature review, which is emerged from health science fields, is another type of literature review which composes an original and valuable work of the research in and of itself. Systematic literature share some common points with traditional literature review such as presenting the available knowledge of the research matter and identify effective research projects and techniques. The distinguishing criteria that it is "summarize existence evidence, identify gaps in current research and provide a framework for positioning research endeavors" (Petticrew and Roberts 2006).

Okoli and Schabram (2010) adapted Arlene Fink's (2005) definition for the research literature review as the definition of systematic literature review: "a systematic, explicit, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners". They explained that in systematic literature collecting data or summarizing other works is not enough as in the case of traditional method, there must be critical analysis to identify and synthesize the existing knowledge.

The previous definition suggested three main points; the first is a systematic, explicit, and reproducible method .The researcher during the analysis stage was looking to identify the architectural interactions when implementing RC system. The second point is to identify, evaluate, and synthesizing, the researcher grouped the identified points logically to serve the main goal of the research of producing a decision-support framework. The third point suggested by the definition is to survey a variety of knowledge sources. This research identifies three sources of knowledge; scholarly work, case studies, and interviews.

In conclusion, architectural knowledge is not all scholarly, human subjectivity is an important factor, thus adapting multi sources of knowledge such as case studies and interviews is crucial to capture this subjectivity and work within the systematic literature review definition.

This research analyzes and surveys the findings of the existing knowledge about RC systems from architectural point of view. As most of the time, mainly scholarly, works related to RC systems discuss the engineering side of the system and neglect the role of the architect in its implementation. Conducting this approach makes the literature analysis done in this research systematic and not traditional.

2.4 The Case Study as a Research Method

Case studies are a major source of knowledge for this research. Case studies provide practical information for the design and implementation of the RC systems. This knowledge influenced the development of the framework. Case studies are used as an instrument to focus on how design decisions were made for the project under investigation. It is important to notice that "the case study is useful for both generating and testing of hypotheses, and is not limited to these research activities alone" (Flyvbjerg 2006).

2.4.1 Case study selection

The information needed from the case studies guide the selection strategy. Flyvbjerg (2006) explained that random sampling selection strategy is not useful when the goal is to collect as much possible information about the case. He suggests that: "the average case study is not always the richest in information". This suggests that 'information-oriented selection', as shown in Figure 2.1, may be appropriate.

Strategies for the Selection of Samples and Cases

Type of Selection	Purpose
A. Random selection	To avoid systematic biases in the sample. The sample's size is decisive for generalization.
1. Random sample	To achieve a representative sample that allows for generalization for the entire population.
2. Stratified sample	To generalize for specially selected subgroups within the population.
B. Information-oriented selection	To maximize the utility of information from small samples and single cases. Cases are selected on the basis of expectations about their information content.
1. Extreme/deviant cases	To obtain information on unusual cases, which can be especially problematic or especially good in a more closely defined sense.
2. Maximum variation cases	To obtain information about the significance of various circumstances for case process and outcome (e.g., three to four cases that are very different on one dimension: size, form of organization, location, budget).
3. Critical cases	To achieve information that permits logical deductions of the type, "If this is (not) valid for this case, then it applies to all (no) cases."
4. Paradigmatic cases	To develop a metaphor or establish a school for the domain that the case concerns.

Figure 2.1. Strategies for the selection of samples and cases
Source: (Flyvbjerg 2006)

Of the four strategies proposed by Flyvbjerg, the 'information-oriented selection' method is most appropriate. This method includes a 'critical cases' selection strategy that is proposed to be the most appropriate strategy. 'Extreme cases' are appropriate for unusual situations which are not the case in this research. The 'Maximum variation cases' selection strategy at first seems to be a good option, but it may direct the research to focus on showing the significant differences of the outcomes rather than helping to build the decision-support framework. Flyvbjerg (2006) explained that 'paradigmatic cases' are appropriate to "operate as a reference point and may function as a focus for the founding of school of thoughts". This strategy would be appropriate for this research if only one building type was being discussed, and that is not the case.

The 'Critical cases' selection strategy was applied as it provided the opportunity for generalization as: "if it is not valid for this case, then it is not valid for any (or only few) cases" (Flyvbjerg 2006).

Identifying critical cases is not an easy task. Flyvbjerg (2006) gave general advice to chose either the 'most' likely or the 'least likely' cases. Then he explains by saying: "cases of the ‘most likely’ type are especially well suited to falsification of propositions, whereas ‘least likely’ cases are most appropriate to tests of verification”.

2.4.2 Research case studies

Table 2.1 summarizes the selected case studies and their criteria. It can be notice that the cases vary in their function, location, size, and the climate zones. This is to enrich and broaden the extracted findings and information. Regardless the limited numbers of projects with RC system in the U.S with accessible information, case studies were selected to cover as many architectural aspects as possible. None of the selected case studies has radiant ceiling panel system, however, this was covered by selecting projects which have chilled slab with active ceiling sides. The New Bangkok International was the only case which was selected from outside the United States, this due to the facts that a) the building has the largest radiant cooling system the world, b) the building is located in a very hot and humid climate zone, and c) the building has high cooling load demands all the time.

Table 2.1. Summary of the case studies main criteria

Project name (Short name)	Project main function	Location	Area (ft²)	Climatic zone	RC system type
Housing for Kripalu Center for Yoga and Health (Yoga Center)	Hotel, Multipurpose hall, Yoga studio	Stockbridge, Massachusetts	33,000	Cool-dry (DOE classification) Humid continental (Köppen climate classification)	Chilled slab with both sides active
Klarchek Information Commons, Loyola University (Digital Library)	Digital library, Class rooms	Chicago, Illinois	70,000	Cool-dry (DOE classification) Humid continental (Köppen climate classification)	Chilled slab with active ceiling
David Brower Center (Brower Center)	Office building	Berkeley, California	45,000	Warm-marine (DOE classification) Mediterranean (Köppen climate classification)	Chilled slab with active ceiling
William J. Clinton Presidential Center (Museum)	Library and Museum	Little Rock, Arkansas	150,000 (105,000 with radiant cooling)	Warm-humid (DOE classification) Humid subtropical (Köppen climate classification)	Chilled slab with active floor (chilled slab)
Suvarnabhumi Airport, the New Bangkok International Airport (Airport)	Airport	Bangkok, Thailand	4,036,000 (1,087,000 with radiant cooling)	Tropical wet and dry (Köppen climate classification)	Chilled slab with active floor (chilled slab)

2.5 Interviews as a Research Method

In the architectural design process, the influence of the human selection and subjectivity is an important factor, even when designing a mechanical system like a RC system. To include this reality while developing the proposed framework, the interview approach as a source of relevant knowledge was performed. The interview was designed in a way to give the designer the ability to express his/her design experience with RC systems within the context of the circumstances surrounding a specific project.

Stake (1995) suggested that case studies should be selected based on their contribution to the understanding of the research question rather than the amount of information they have. The same criteria could be applied in the selection process for the questionnaire respondents. Since this study is mainly to capture the knowledge related to the decisions made when implementing and designing RC systems in any given space from an architectural point of view, architects and engineers involved in such projects are the main candidates.

Oppenheim (1992) explained that to ensure consistency during the conduction of the questionnaire, all respondents have to be contacted using the same communication format. In this research, all interviewees were contacted by phone and were asked the same set of questions as explained in the next section.

2.5.1 Structure of the questionnaire

The interview's questions, attached in appendix A, were divided into five different groups of questions:

a) Group no. 1: Introductory questions; to establish a background about respondents, the role he/she played in implementing the RC system, the system type he/she used, and to identify the system's endogenous variables.
b) Group no. 2: Design process; to identify the factors affecting the design process, identify the system's exogenous variables, and the limitations/ constraints he/she or the designer may face when implementing a RC system.
c) Group no. 3: Relationships with thermal comfort and IAQ; to study the direct relationship between RC systems and thermal comfort and IAQ. Also, to extract rules of thumb, recommendations, and solutions.

d) Group no. 4: Relationships with other Building Performance Mandates (BPMs); to study the relationship between RC systems and the other BPM. Also, to extract rules of thumb, recommendations, and solutions.
e) Group no. 5: Conclusion; to express further information and comments that was not covered during the interview.

2.5.2 Pre-test (quality test)

Oppenheim (1992) mentioned in his book that: "piloting can help us not only with the wording of questions but also with procedural matters such as the design of a letter of introduction…, the ordering of the question sequences and the reduction of non-response rate". He also added that "each survey research presents its own problems and difficulties, and expert advice or spurious orthodoxy are no substitutes for well-organized pilot work"

However, due to the limited numbers of participants the pre-test interview was not performed, and the following steps were conducted instead:

a) After setting the primary goals of the questionnaire and constructing the first draft, the questionnaire was reviewed by my committee members as many of them have good experience in the knowledge-capturing field.
b) Following this, the questionnaire was reviewed by a specialist in surveys and questionnaires in the Center for Survey Research at Virginia Tech.

2.5.3 Minimizing bias

The questions were designed to be open-ended. Stasko (1997) explained the advantages of this type of question by revealing unprompted opinions, and there is no predetermined set of responses as the interviewee is free to answer the way he/she chooses. He added that: "open format questions are good for soliciting subjective data or when the range of responses is not tightly defined. An obvious advantage is that the variety of responses should be wider and more truly reflect the opinions of the respondents".

Stasko (1997) explained one type of bias which he called "prestige bias". He defined this as: "the tendency for respondents to answer in a way that makes them feel better. People may not lie directly, but may try to put a better light on themselves". However, the solution he suggested is to make the questionnaire as private as possible and to let participants know about this confidentiality. He added: “telephone interviews are better than person-to-person interviews, and written questionnaires mailed to participants are even better still. The farther away the critical eye of the researcher is, the more honest the answers”.

Beed and Stimson (1985) identified another kind of bias as response bias. “Response bias comes about because the respondent reports either incompletely or inaccurately the information that is requested from him/her. This may be due to the wording of the question; it may also be due to the kind of information requested”. According to them, there is no easy solution for this, but it may be reduced by careful selection of the participants and through a quality-test questionnaire (pre-test).

2.6 Development of the Framework: A Combined Approach

Figure 2.2 shows the research stages, the research approach (grounded theory), and the methodological (systematical literature review, case studies, and interviews) relationships.

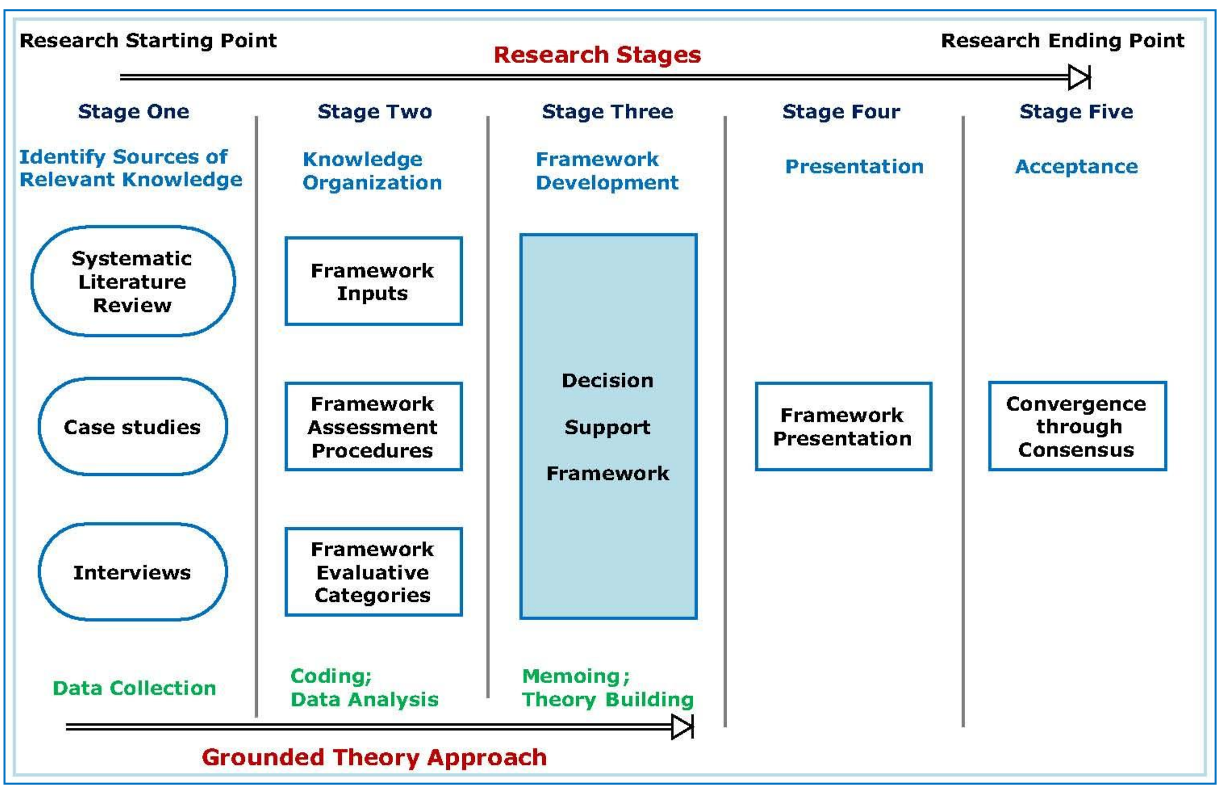


Figure 2.2. Research stages and methodology

In this research and as Figure 2.2 illustrates, to develop the framework, five major steps were completed:

a) Identify sources of relevant knowledge based on a grounded theory approach where the theory, in this case the framework, emerges at the end and is not hypothesized at the beginning. This step was conducted using the following techniques:

   i. Systematical literature review; which is intended to determine the current state of the knowledge in the area of study. It will identify tools, inputs, procedures, and evaluative categories related to the design and implementation of RC systems in spaces/buildings.

   ii. Case studies of as-built projects. Stake (1995) identified two main types of case studies; intrinsic and instrumental case studies. The former is where the understanding of the case study is the primary goal and the later type is where the case study is undertaken in the service of an overriding research agenda. Instrumental case studies were used in this research. They are to fill the gaps from the literature review, provide practical information, and they may help in suggesting new inputs for the framework.

   iii. The interview was designed to capture the experts' knowledge related to RC systems design and implementation. The interview targeted mainly architects and engineers who were involved in RC system design. The goal of this interview was to expand and validate the inputs and variables of the decision-making procedures.

b) Knowledge organization; in this step, the captured knowledge through the previous techniques is categorized into three groups; framework inputs, framework evaluative categories, and framework assessment procedures. Framework inputs are the variables under investigation and include RC systems endogenous and exogenous variables. Framework evaluative categories are the performance of the RC system in light of the building mandates. Framework assessment procedures are systematic means of analysis which link the framework inputs to the framework evaluative categories.

c) Develop the framework with its inputs, assessment procedures, and evaluative categories and map them all as a decision support tool.

d) Presenting the proposed framework using a graphical language. The decision tree software was used in this research.
e) The final step is presenting the proposed framework to stakeholders and getting their comments and feedback.

In conclusion, to capture the human factors when designing and implementing RC systems to develop the proposed framework, two research tactics were used; instrumental case studies and open-ended interviews. These tactics were used as an instrument to focus on how the design decisions were made. Case studies are selected based on specific criteria which would provide opportunity for generalization. The interviews' open-ended questions were designed and focused to capture the design process and identifying the different variables.

2.7 Graphical Representation

The decision-support framework for the use and implementation of RC systems will serve a potentially broad set of users: architects, HVAC engineers, owners, building managers, etc., therefore it is important to use a language accessible to all users. A graphical language could serve this purpose.

As the framework is a decision-support tool which will model different scenarios of decisions and their consequences, a graphical language such as a 'decision tree' could support this purpose and help visually illustrate the framework. The similarities in the characteristics of applying an analytical decision-support tool and the implementation of a RC system such as complexity, uncertainty, and multiple and competing objectives, makes the use of the graphical language of a decision tree an appropriate tool. A decision tree can encapsulate big problems into simple diagrams and can explain the consequences of each alternative. Section 4.4 discusses the research graphical representation in more details.

3 SOURCES OF RELEVANT KNOWLEDGE

As explained in the research methodology section, in this chapter the knowledge related to the design and implementation of RC systems will be captured and analyzed. This knowledge may be defined as: the endogenous and exogenous variables of the RC system, the relevant design performance mandates, barriers and constraints, and potential advantages and benefits of the system implementation. This knowledge will be then mapped to a decision-support framework.

The sources of the relevant knowledge will be identified through three different research methods:

a) Systematic literature review.
b) Case studies
c) Interviews with the system expertise.

3.1 Sources of Relevant Knowledge: Systematic Literature Review

This section is to identify and analyze variables related to the following topics:

a) Part one: RC systems
b) Part two: Architectural design factors, namely; Building Performance Mandates (BPM)
c) Part three: Energy consumption and cost
d) Part four: Decision-support systems and the decision-making process

3.1.1 Part One: RC systems

In this section, the relevant variables which are proceeding from within the RC system will be identified. These variables are called the endogenous variables.

3.1.1.1 RC system variables

The RC system is a mechanical system comprising many components with many possible configurations. The variables associated with the design and operations of the system are many and include the following:

3.1.1.1.1 Cooling capacity

Cooling capacity is the capacity of the system to absorb heat from the conditioned space(s). Many factors play a major role in determining the cooling capacity of the RC system. Those factors include:

a) Heat exchange between the cooled surface and the space: convection and/or radiant heat exchange.
b) Heat conduction between the cooled surface and the pipes carrying the cold water. The heat conduction depends on: surface material, tube material, surface thickness, and spacing between tubes.
c) Heat transport by water which depends on: water flow rate, and temperature difference between water supply and return (Δ T).

However, when considering the system cooling capacity, some of these factors seem to be beyond the concern of the architect, where the cooling capacity value of the system final configuration is the most important. Due to the limitation of the RC system cooling capacity may impose some limitations as explained in section 4.5.1.

Chilled slab:

Olesen (1997) mentioned based on experimental results that the maximum cooling capacity for a cooling floor is 13 Btu/h· ft^2 [42 W/m^2], based on the recommended lower limit of floor temperature of 68 ˚F, and recommended an upper limit of the operative temperature of 79 ˚F for rooms occupied by people with mainly sedentary activities and summer clothing. Moore, Bauman, and Huizenga (2006) mentioned in their report based on a study done by Mikler in 1999 that the cooling capacity for radiant slab is approximately 24 Btu/h· ft^2 [76 W/m^2] at a surface temperature of 64 ˚F, and this is only the sensible cooling capacity which does not include the associated ventilation cooling capacity. Lowering the floor surface temperature below the ‘allowable’ minimum temperature suggested by ANSI/ASHRAE Standard 55-2004, 66.2 °F, is a special design case.

Andreas Limberg (personal communication, April 15, 2011) mentioned that in cases where solar radiation is hitting the space’ floor directly, the chilled slab system could be designed to remove this extra heat by lowering the supply water temperature to the slab. This will increase the temperature difference between supply and return water (ΔT) and thus increasing the chilled slab ability to remove the extra solar heat without lowering its surface temperature below the recommended temperature.

Ceiling system:

In the case of a radiant ceiling cooling panel system (RCCP), Conroy and Mumma (2001) explained that the system’s radiant cooling capacity, or sensible cooling capacity, will be about 13 Btu/h· ft² [41.01 W/m²], based on an average operative temperature of 75 ˚F and a system surface temperature of 60 ˚F, along with 11 Btu/h· ft² [34.7 W/m²] due to convection, that gives a total cooling capacity of 24 Btu/h· ft² [75.7 W/m²] under the mentioned conditions.

Moore, Bauman, and Huizenga (2006) claimed that the cooling capacity for ceiling systems is roughly 30 Btu/h· ft² [95 W/m²] not including the associated ventilation system/strategy cooling capacity. However, they did not explain the circumstances in which this capacity could be achieved.

In general, overhead cooling surfaces are more effective than chilled slabs as the heat transfer coefficient for ceiling systems are bigger than in chilled slab systems, mainly due to the view factor as explained in section 3.1.2.3.6. The exceptions are when the space ceiling is very high, or when the slab system is designed to remove the heat of the direct sunbeams hitting the space, so its surface temperature could be lowered below the recommended temperature of 68 ˚F.

The convection heat transfer in RCCP systems is relatively higher than in chilled slab systems; that is partly due to the relatively lower surface temperature in RCCP systems. This would make the total cooling capacity of RCCP systems higher. Also, in the ceiling systems natural convection will happen due to the buoyancy effect; cool air falls down and is replaced with warmer air close to the cooled surface. This would also increase the total cooling capacity of the RCCP system. Figure 3.1 summarizes the previous discussion:

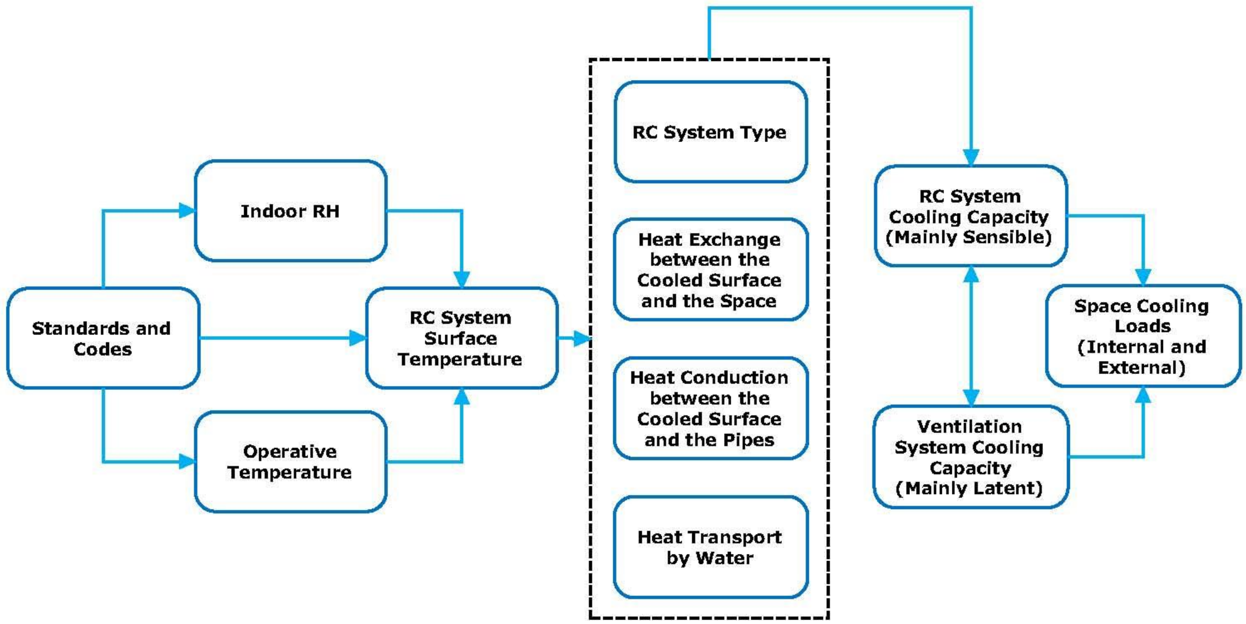


Figure 3.1. RC systems cooling capacity

3.1.1.1.2 Surface temperature

The system surface temperature is an important and critical variable in designing RC systems, as it will affect the system performance. The surface temperature has to stay within the acceptable limits defined by codes to provide the thermal comfort environment. Also, it has to stay above the indoor air dew point temperature mainly to eliminate the possibility of condensation, and to maintain the material integrity. These conditions may affect the system cooling capacity.

Chilled slab:

In radiant slab systems, discomfort will occur if the surface temperature is too low in the cooling mode or too high in the heating mode. According to ASHRAE (2009) 20% of the occupants will be thermally dissatisfied if the floor temperature is out of the range of 60 ˚F to 90 ˚F for rooms occupied by sedentary or standing people wearing normal shoes. According to ANSI/ASHRAE Standard 55-2004, the “allowable range of floor temperature” is between 66.2 °F and 84.2 °F. However, ASHRAE (2009) mentioned that the optimal temperature is 77 ˚F for sedentary and 73.5 ˚F for standing or walking persons. This can limit the cooling capacity or influence the design of the chilled slab system.

Ceiling system:

For ceiling systems, where there is no direct contact between the occupants and the cold surfaces, the limitations on the surface temperature are due to radiant temperature asymmetry and indoor air dew point temperature. Figure 3.2 summarizes the previous discussion:

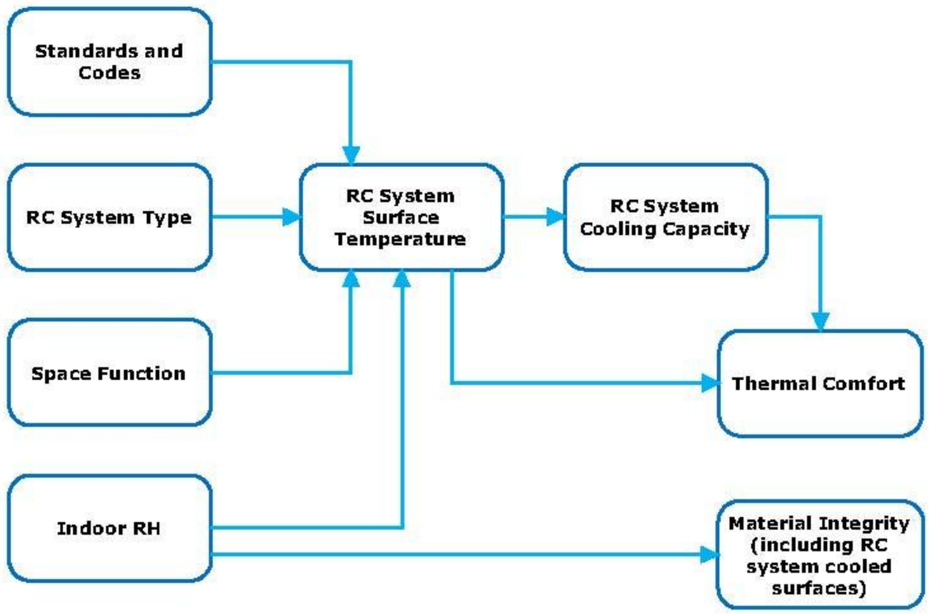


Figure 3.2. RC systems surface temperature

3.1.1.1.3 Control

Control refers to the ability to have different conditions in individual spaces when using RC systems. Those conditions may refer to cooling capacity, surface temperature, and dew point temperature. Failure in controlling any of these issues may lead to serious problems or even system failure.

Chilled slab:

A chilled slab is typically slow to react to rapid changes in the load, which is mainly due to the high thermal inertia of the system (Moore, Bauman, and Huizenga 2006). The chilled slab system takes relatively longer time than an RCCP system before its surface reaches the desired temperature. Therefore, addressing rapid changes in cooling loads such as solar gains or large number of occupants for short periods of time should be considered in the early stages of the design. In some cases an additional cooling system is needed to address such rapid changes in specific zones.

Ceiling system:

Even though RCCP cooling capacity is limited, their response time is generally quicker than chilled slab systems as their thermal inertia is relatively low, and the system surface temperature could reach the desired temperature within a short time. As a result, ceiling systems can handle load variation more efficiently. Figure 3.3 summarizes the previous discussion:

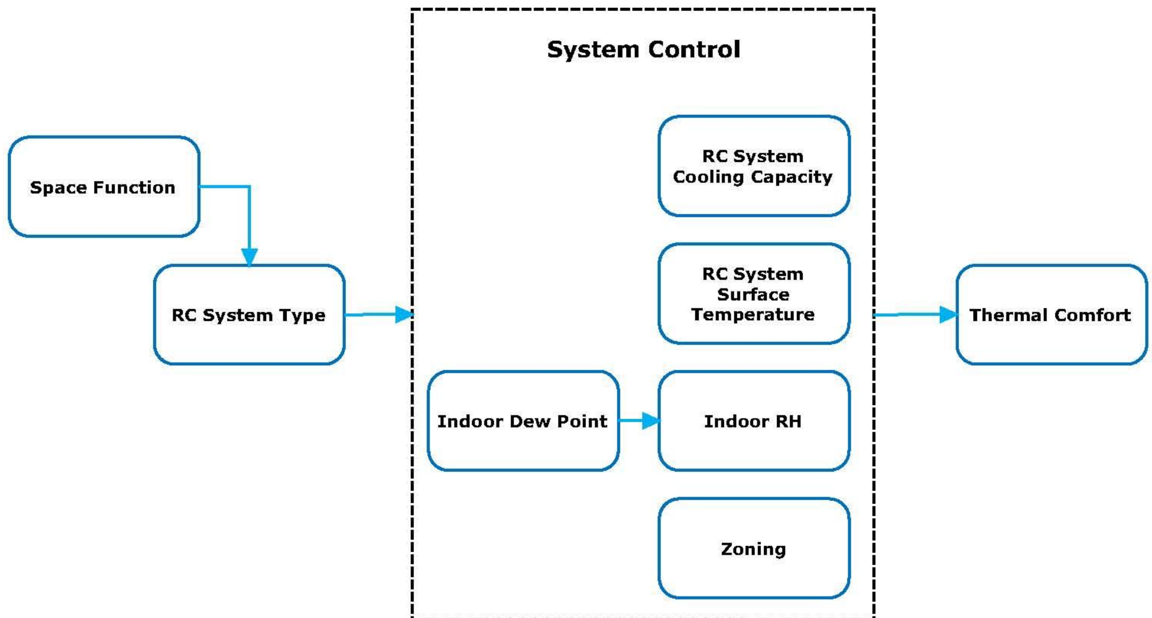


Figure 3.3. RC systems control issue

3.1.1.1.4 Physical properties

The performance of the RC system is partially related to its physical properties. Vangtook and Chirarattananon (2006) explained the factors affecting the rate of radiant energy heat transfer or cooling capacity, and they are "temperature (of the emitting surfaces and the receivers), emittance (of the radiating surfaces), reflectance, absorptance and transmittance (of the receivers), and view factors between the emitting surfaces and the receivers (viewing angle/factor of the occupant to the radiant sources)" .

The view factor between the system cooled surface and the heat sources will affect the RC system cooling capacity. This makes the cooled surface dimension and its location important implementing the system inside the space. Also, due to the fact that RC system will occupy large areas of the interior space, this might affect the space room acoustics environment and the indoor visual (lighting) environment (Moore, Bauman, and Huizenga 2006). Figure 3.4 summarizes the previous discussion:

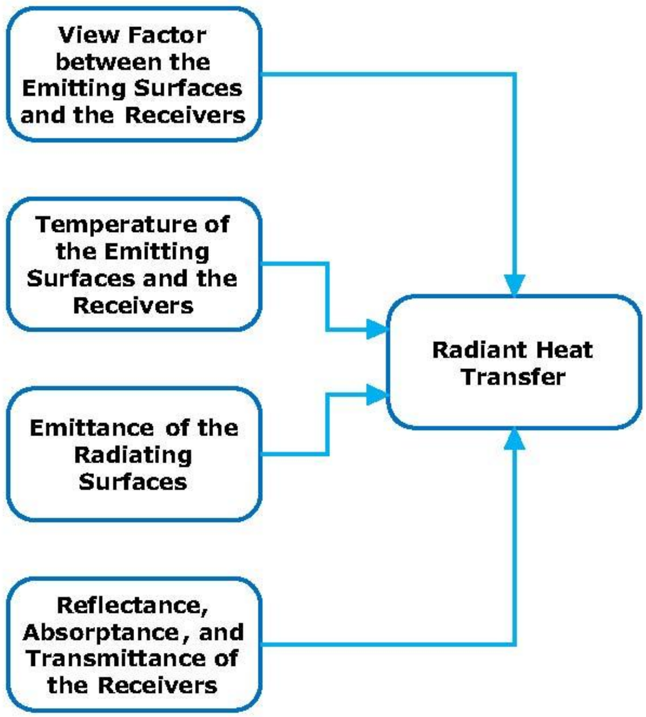


Figure 3.4. RC systems physical properties

Table 3.1 summarizes the RC system variables discussed previously.

Table 3.1. Summary of RC system variables

Variables	Chilled Slab Systems	Radiant Cooling Ceiling Panel (RCCP) Systems
Cooling Capacity	Sensible: 13 Btu/h· ft² [42 W/m²], at a surface temperature of 68 °F (Olesen, 1997) Sensible: 24 Btu/h· ft² [76 W/m²], at a surface temperature of 64 °F (Moore, Bauman, and Huizenga, 2006)	Sensible: 13 Btu/h· ft² [41.01 W/m²], latent: 11 Btu/h· ft² [34.7 W/m²], at surface temperature of 60 °F (Conroy and Mumma, 2001) Sensible: 30 Btu/h· ft² [95 W/m²] (Moore, Bauman, and Huizenga, 2006)
Surface Temperature	Minimum temperature is 66.2 °F (ANSI/ASHRAE Standard 55-2004)	Limited by: Radiant temperature asymmetry Indoor air dew point temperature
Control	Slow to react to rapid changes in loads	Quicker response time

3.1.2 Part Two: Architectural design factors

3.1.2.1 Introduction

Walsh (2000) defined performance as the amount of achievement relevant to the assigned targets. Targets, which may come in different forms such as standards, quotas, service levels, etc, are something aimed at or to be aimed at, as a current or future level of achievement.

In the building sector, the expectations placed upon a building may in part be defined in terms of human comfort, health, safety, and performance (Rush 1986). Those expectations take the form of building codes and standards, design specifications, and construction contracts intended to guide the building process to achieve the desired expectations.

Rush (1986) said: “buildings don’t perform; the people who design, build, and use them do.” By this he means architects, designers, and decision-makers design and build their buildings to get what they want and need from them. According to him, this suggested that the users’ needs are central to the design and should not be external to the building process. However, what people want from a building varies from one situation to another based on many factors, including social, cultural, age, etc.

An important step after setting the building's performance targets is to evaluate the level of achievement for those targets. The evaluation of building performance could be classified as; a) assessing current building performance, and b) predicting future building performance. This research will focus on predicting future building performance (new construction) with the implementation of RC systems.

Wong and Jan (2003), and Douglas (1994) divided building performance evaluation into three stages in terms of time; pre-construction stage, during the construction stage, and post construction. Each of these stages engages different techniques as shown in Table 3.2:

Table 3.2. Construction stage and suggested evaluation techniques
Source: adapted from (Douglas 1994)

Stage	Techniques
Pre-construction	Value management Technical audits: involve analyses of vulnerable or key details of proposed building scheme. The aim is to prevent any potential failure.
During construction	Building performance cost-in-use model; value management.
Post construction	Post-occupancy evaluation (POE); Building quality assessment (BQA); Building performance cost-in-use model; Property efficiency appraisal (PEA); ORBIT 2.1

However, Douglas (1994) mentioned that for each stage there are two levels of performance: the Micro-level, where the assessment is dealing with specific parts of the building and the Macro-level assessment where the total performance of the building is under investigation. Therefore it is important to determine the performance criteria for the building to assist the decision-making process and to establish assessment criteria. Douglas (1994) suggested that "building professionals should be wary of imposing their own list of criteria on the providers and user of property. Rather they should identify the relevant criteria based on established or recognized authorities".

A long list of building performance criteria could be constructed according to different building types, owner needs, and authorities' jurisdictions. This research will adapt the building performance mandates suggested by Richard Rush in his book *The Building Systems Integration Handbook*. This list was developed based on a "manageable definition of the building performance criteria such as ISO/TC 59 [*Performance standards in building- Principles for their preparation and factors to be considered* (ISO 6241 1984)]." Each of these performance mandates was defined by its physiological, psychological, sociological, and economical needs as mentioned in '*Performance Concept in Buildings by National Bureau of Standards'* by Foster (1972).

These performance mandates presented in Figure 3.5 include; thermal performance, indoor air quality (IAQ), acoustical performance, spatial performance, visual performance, and building integrity. "The first five mandates comprise interior occupancy requirements and the elemental parameters of health, safety, and well being in relation to the spatial quality, thermal quality, air quality, acoustical quality, and visual quality of the space being designed" (Rush 1986). The last mandate, building integrity, is dealing with "protection of the building's appearance and of its mechanical and physical properties from environmental degradation" (Foster 1972). This research will focus on the first five mandates as the evaluative categories of the design and implementation of the RC systems as shown in Figure 3.6.

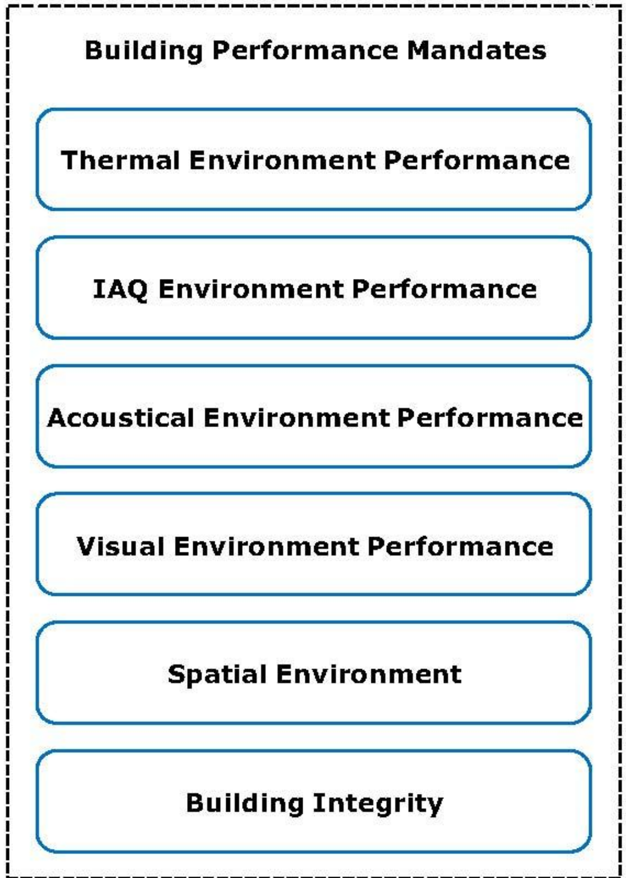


Figure 3.5. The building performance mandates (BPM) as defined
Source: Adapted from (Rush 1986)

The reasons for focusing on these specific performance mandates are that the main purpose of installing a RC system is to provide thermal comfort, but at the same time, there are other performance mandates to be achieved in the same interior space. Understanding the relationships between all these performance mandates under the existence of a RC system will help architects and HVAC system designers. This understanding will enhance the overall performance of the indoor environment under investigation. Also, this understanding will promote the use of RC systems by providing a systematical way of evaluating the applicability of the system in any given space from an architectural point of view.

The building performance mandates mentioned previously are not meant to be definitive or restrictive, rather they are intended to reduce subjectivity and to provide a consistent framework or a decision analysis tool for implementing a RC system, or when comparing two different RC systems.

In addition to these performance mandates, RC systems or any other building system must be evaluated in terms of their cost and energy consumption as they are, in the real world, important factors in any system implementation decision. However, these two additional mandates are not be included in the framework as stated previously. Future research may include these two factors in the decision-support framework. However, this research discusses these two factors in section 3.1.3.

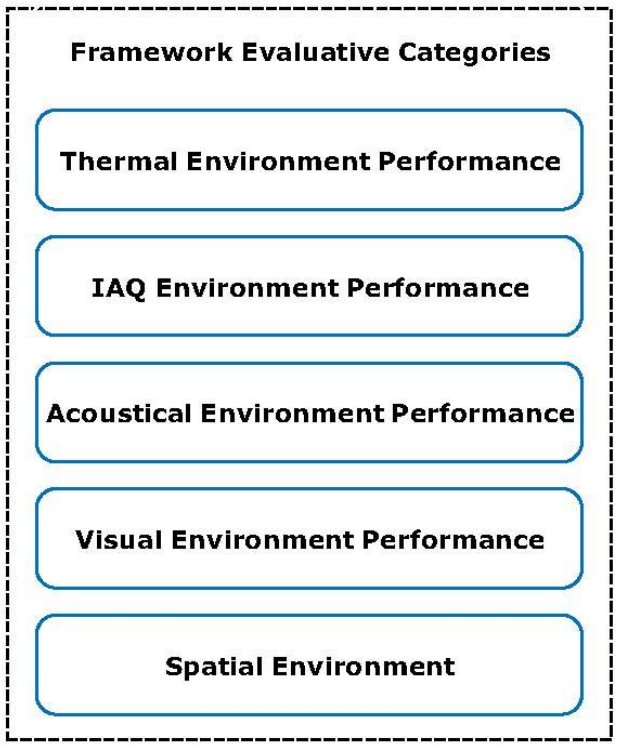


Figure 3.6. The framework evaluative categories

3.1.2.2 Building Performance Mandates (BPMs)

3.1.2.2.1 Introduction

Rush (1986) divided BPMs into six categories; thermal performance, air quality, acoustical performance, spatial performance, visual performance, and building integrity. Under each one of these performance categories he included many topics as shown in Figure 3.7. This research focuses only on the categories and topics highlighted as shown in Figure 3.7. These categories and topics are used as the evaluative criteria for the implementing RC systems in any given space.

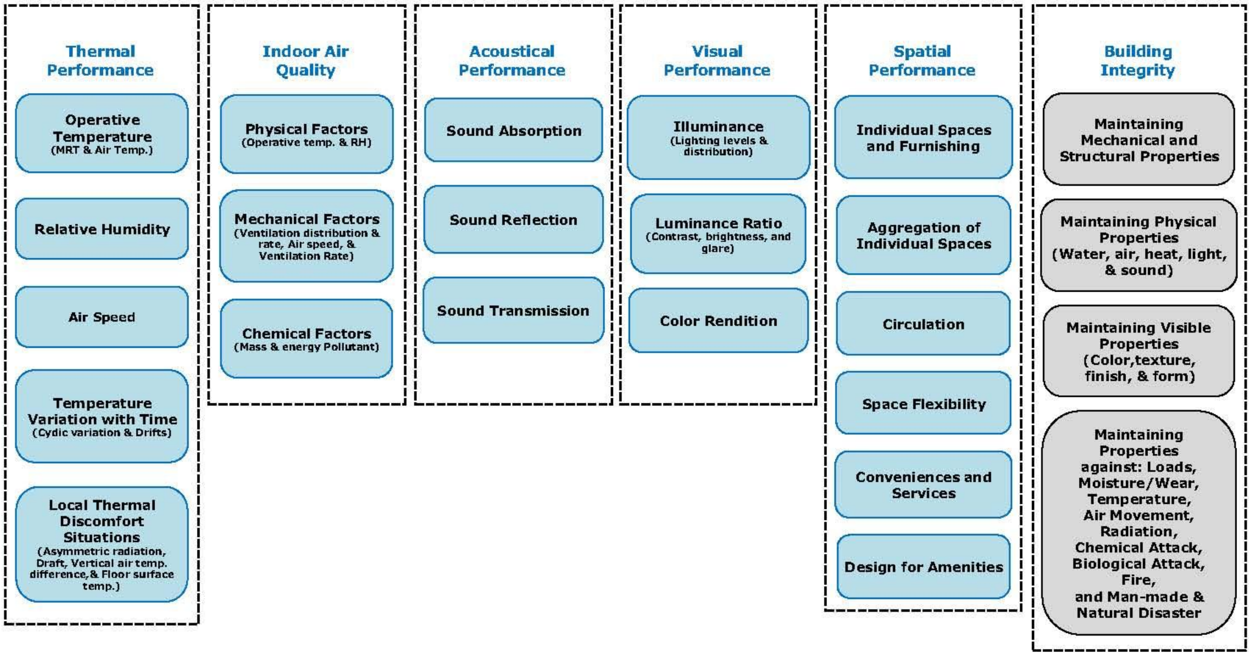


Figure 3.7. Relevant Building Performance Mandates (BPM)
Source: Adapted from (Rush 1986)

Rush (1986) explained in his book the reasons behind the emergence of the building performance mandates as:

> *Responsibility for delivering these occupancy performance mandates has been divided largely along disciplinary lines. Architects have taken primary responsibility for spatial quality and delegated responsibility to mechanical engineers for thermal quality and air quality, to lighting engineers for visual quality, and to acoustical engineers for acoustical quality. One of the primary motivating forces for system integration is performance. Such design criteria as energy or resource conservation, functional appropriateness, strength and stability, durability, fire safety, weathertightness, visual comfort, acoustical comfort, and economic efficacy , are only delivered when the entire building performs as an integrated whole (p.232).*

A concern for this research is that decisions related to RC systems involve the architect as well as other professionals. While the architect is mainly concerned with the spatial quality of the solution; he/she also has to acknowledge that other systems will be used to achieve the desired level of performance. This research mainly investigates the consequences of implementing RC systems in any given space through the previously mentioned BPMs, with the resulting framework being applicable as an aid to decision-makers involved in the building design and construction industry.

Rush (1986) defined performance as: “the measurement of achievement against intention”. All designers want their buildings to perform well when measuring BPMs. However achieving a high level of performance for all mandates is not an easy task due to the following reasons:

a) Different buildings have different functions which influence the performance mandates differently. For example, museums often require a higher level of visual performance, while hospitals may be more concerned with thermal comfort and IAQ.
b) Taking one performance mandate to its highest performance level may adversely affect the performance level of other mandates. For example, reducing the glass area in the northern façade to minimize heat loss in winter will affect the amount of natural light penetrating the space from that side.
c) Achieving a performance mandate is not a single decision making process: it typically involves the integration of many building systems while balancing multiple performance mandates. The BPMs interactions with the building’s systems are shown in Figure 3.8.

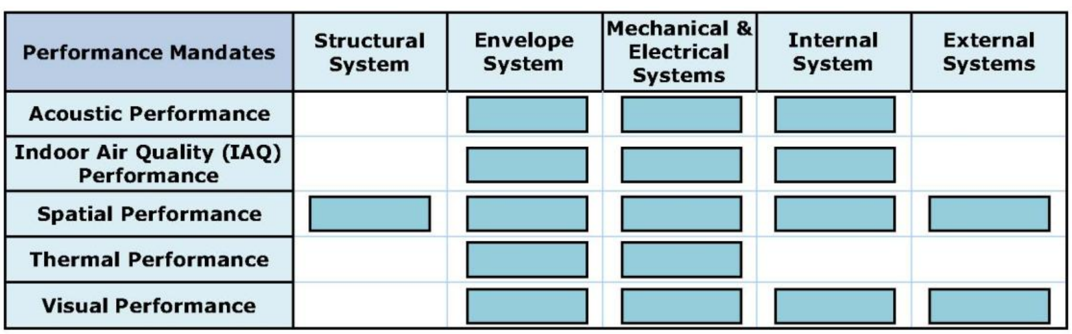


Figure 3.8. BPM interaction with different building systems
Source: Adapted from (Rush 1986)

From the previous figure one may notice the following:

a) The contents are subject to variation, but the concepts it present hold while developing the framework.

b) Building performance mandates cannot be understood in isolation from each other. They are related through multiple effects. Therefore, studying the thermal performance alone under the existence of the RC system will not provide a complete picture of the micro-level environment.

c) The decision-maker(s) has to decide which system(s) to use based on the differences of their performance to meet the building mandate(s) requirements.

When considering thermal comfort and IAQ, the influencing factors could be considered by simple physical equations or by codes and standard procedures which called assessment procedure. These assessment procedures may have other variables within them, or/and must work within limits. The relationship between these variables and RC systems are explained. Additionally, the relationship between the RC system and the BPM are discussed, as understanding the consequences of implementing a RC system is a main goal of this research.

3.1.2.3 Thermal comfort

3.1.2.3.1 Introduction: thermal comfort approaches

Thermal comfort as defined in ASHRAE 2009 and in ANSI/ASHRAE 55 2004 is: "That condition of mind which expresses satisfaction with the thermal environment". This definition, leaves the term "condition of mind" loosely defined and open for different interpretations. The ultimate principle of installing any cooling system, including RC systems, is to provide conditions for human thermal comfort (ASHRAE 2009). On the other hand, this open definition raises the challenges for architects and cooling systems' engineers of predicting the thermal comfort conditions in built environments without asking the occupants about their thermal comfort sensation; cold, cool, slightly cool, neutral, slightly warm, warm, or hot.

In the search to predict the human thermal comfort conditions and to determine the complex nature of these conditions, many, studies, models, and theories have been made and developed. However, they can be divided into two major groups: the heat balance approach and the adaptive model approach.

Following the heat balance approach, which is based on laboratory studies, the primary variables affecting the thermal comfort condition include: air temperature (ºF), radiant temperature (ºF), relative humidity (%), air speed (f/s), metabolic rate (met), and clothing insulation (clo). However, all of these variables must be maintained simultaneously to avoid thermal discomfort (ASHRAE 2009; ANSI/ASHRAE 55 2004; Watson and Chapman 2002). The main principle of this approach is that the "the net heat production (M– W) is transferred to the environment through the skin surface (q_{sk}) and respiratory tract (q_{res}) with any surplus or deficit stored (S), causing the body's temperature to rise or fall" (ASHRAE 2009). This principle is expressed in equation 3.1 and Figure 3.9:

$$\begin{aligned} M - W &= q_{sk} + q_{res} + S \\ &= (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \end{aligned} \qquad \text{Eq. (3.1)}$$

Where:

M = rate of metabolic heat production, Btu/h·ft2
W = rate of mechanical work accomplished, Btu/h· ft2
q_{sk} = total rate of heat loss from skin, Btu/h· ft2
q_{res} = total rate of heat loss through respiration, Btu/h· ft2
C + R = sensible heat loss from skin, Btu/h· ft^2
E_{sk} = total rate of evaporative heat loss from skin, Btu/h· ft^2
C_{res} = rate of convective heat loss from respiration, Btu/h·ft^2
E_{res} = rate of evaporative heat loss from respiration, Btu/h·ft^2
S_{sk} = rate of heat storage in skin compartment, Btu/h·ft^2
S_{cr} = rate of heat storage in core compartment, Btu/h·ft^2

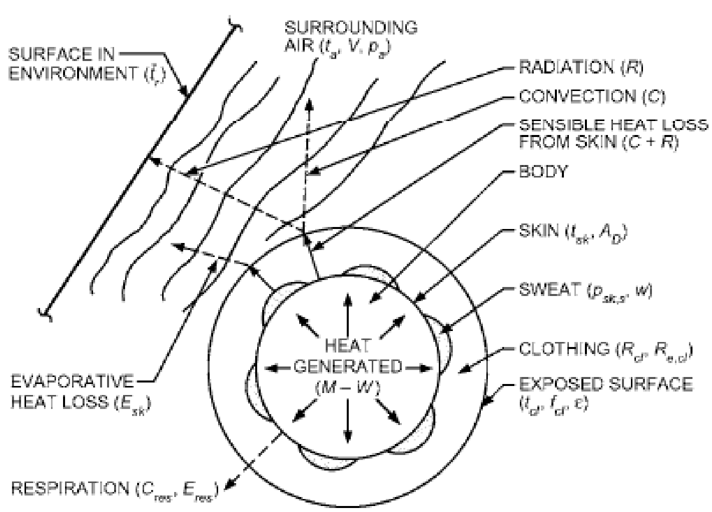


Figure 3.9. Thermal interaction of human body and environment
Source: (ASHRAE 2009)

On the other hand, following the adaptive model approach, which is based on field studies, the fundamental principle of this approach is expressed by the following statement: “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Yao, Li, and Liu 2009). De Dear and Brager (1998) mentioned three main actions of that take place, and they are: physiological adaptation, psychological adaption, and behavioral adjustment.

Standards such as ANSI/ASHRAE 55-2004 and ISO 7730-2005 established acceptable limits for each thermal comfort factor based on the heat balance approach. Even these standards have come to be considered as universally applicable across all building types, climate zones, and population. Many researchers argued that these limits cannot be ‘internationalized’ nor be applied worldwide, as other factors have to be included such as the cultural, climatic, social, and contextual dimensions of comfort (Kempton and Lutzehiser 1992). Brager and de Dear (1997) stated: “ the role of expectation in thermal comfort research was acknowledged in the earlier work of McIntyre (1980), who stated that: a person’s reaction to a temperature, which is less than perfect, will depend very much on his expectations, personality, and what else he is doing at the time”.

As Standards ANSI/ASHRAE 55-2004 and ISO 7730-2005, which are based on the heat balance approach, are the standards used in the U.S. they will be applied for this research. However, Standard ANSI/ASHRAE 55-2004 recognizes the adaptive approach of thermal comfort as an optional method, while stating clearly that this approach is not applicable in mechanically cooled spaces, including RC systems. Figure 3.10 summarizes the previous discussion:

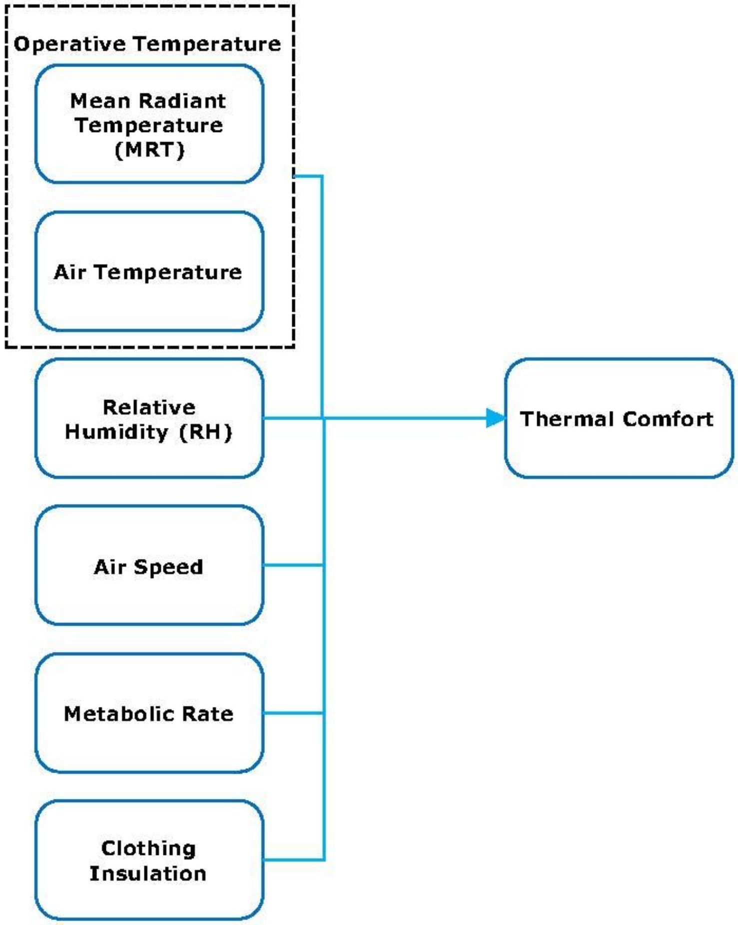


Figure 3.10. The primary variables affecting the thermal comfort environment condition following the heat balance approach

3.1.2.3.2 Thermal comfort and occupants

Regardless of the means to measure or predict the thermal comfort condition, failure to provide acceptable conditions could cause serious problems for building occupants. Ramsey and Beshir (1997) state: “excessively hot or cold environments can affect motor and cognitive behavior of individuals. Extremely hot conditions can lead to loss of performance capacity and slow production output, while excessively cold environments can affect manual agility, and sometimes are associated with pain.”

Providing thermally comfortable environments for the occupants helps in increasing their performance as shown in Figure 3.11. Thermal comfort is also responsible for increasing productivity and supports better health, comfort, and satisfaction (O. Seppänen and W. J. Fisk 2002; Leaman and Bordass 2005).

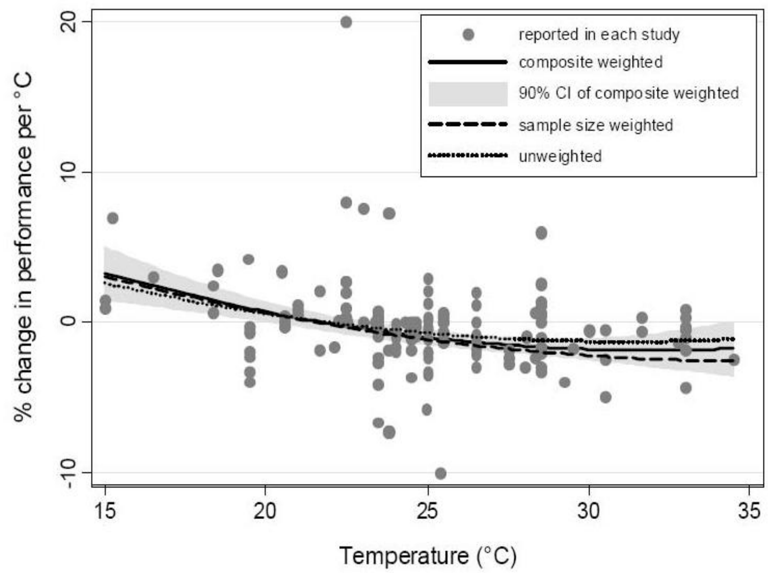


Figure 3.11. Percentage change in performance vs. temperature. Positive values indicate improved performance and negative values deteriorated performance with increase in temperature Source: (Seppanen, Fisk, and Lei 2006)

3.1.2.3.3 Conditions for thermal comfort

The six primary factors influencing thermal comfort are: air temperature, mean radiant temperature, humidity, air speed, metabolic rate, and clothing insulation (ANSI/ASHRAE 55 2004). The first four factors are primarily the responsibility of the designer, while he/she has no control over the last two factors more than acknowledging and predicting them when designing the space. Metabolic rate and clothing insulation are occupant-dependent and differ from one situation to another even for the same building type. The RC system performance will be examined against these factors. Figure 3.12 summarizes the previous discussion:

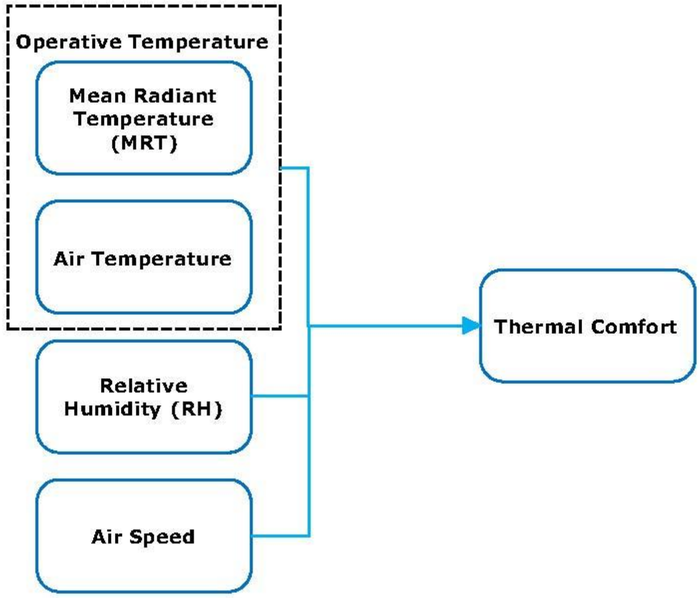


Figure 3.12. The variables affecting the thermal comfort and lay within the responsibilities of the designer

3.1.2.3.4 Operative temperature (t_o)

ANSI/ASHRAE 55 (2004) defined operative temperature as : "the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment." It could be also understood as the combination of air temperature and mean radiant temperature as shown in Eq. 3.2.

$$t_o = h_r\, t_r + h_c\, t_a / h_r + h_c \qquad \text{Eq. (3.2)}$$

Where:
t_o: Operative Temperature
h_r :Linear radiative heat transfer coefficient, Btu/h· ft²·°F
t_r :Mean radiant temperature, °F
h_c :Convective heat transfer coefficient, Btu/h· ft²·°F
t_a :Air temperature, °F

For occupants with metabolic rates between 1.0 met and 1.3 met, no direct sunlight, and air velocity less than 40 fpm, t_o may be approximated with accepted accuracy as in Eq. 3.3:

$$t_o = (t_a + t_r) / 2 \qquad \text{Eq. (3.3)}$$

The range of operative temperature according to ANSI/ASHRAE 55 (2004) and ISO 7730 (2005) is presented in Figure 3.13. These ranges are for 80% occupant acceptability. These limits are for people wearing clothing with a clo value of 1.0 and 0.5 during activity levels that result in metabolic rates between 1.1 met and 1.3 met, and with air speed ≤ 40 fpm (0.20 m/s). See Figure 3.13.

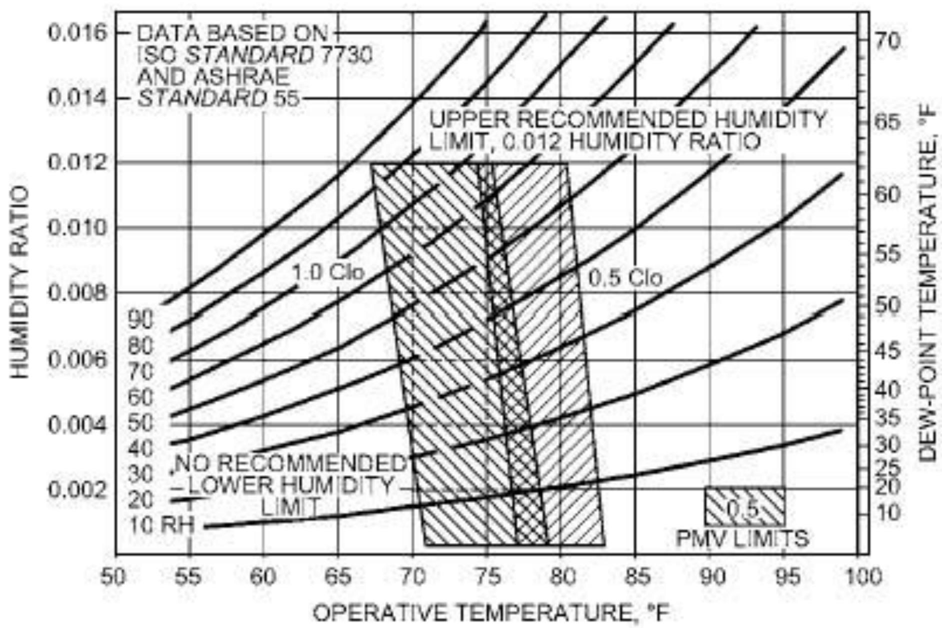


Figure 3.13. ASHRAE summer and winter comfort zones
Source: (ASHRAE 2009)

For intermediate values of clothing insulation, linear interpolation may be used as in equations 3.4 and 3.5:

$$T_{min,\, Icl} = [I_{cl} - 0.5_{\ clo})\, T_{min,\, 1.0\, clo} + (1.0\ \text{clo} - I_{cl})\, T_{min,\, o.5\, clo}] / 0.5\ \text{clo} \qquad \text{Eq. (3.4)}$$

$$T_{max,\, Icl} = [I_{cl} - 0.5_{\ clo})\, T_{max,\, 1.0\, clo} + (1.0\ \text{clo} - I_{cl})\, T_{max,\, o.5\, clo}] / 0.5\ \text{clo} \qquad \text{Eq. (3.5)}$$

Where:
$T_{min,\, Icl}$ *: lower operative temperature limit for clothing insulation* I_{cl}
$T_{max,\, Icl}$ *: upper operative temperature limit for clothing insulation* I_{cl}
I_{cl} *: thermal insulation of the clothing in question (clo)*

Also, air speed greater than 40 fpm (0.20 m/s) may be used to shift the upper operative temperature limit of the comfort zone in circumstances explained in section 3.1.2.3.8.

In conclusion, the variables affecting the operative temperature are the air temperature, the mean radiant temperature, thermal insulation of the clothes, and person metabolic rate. Figure 3.14 summarizes the previous discussion:

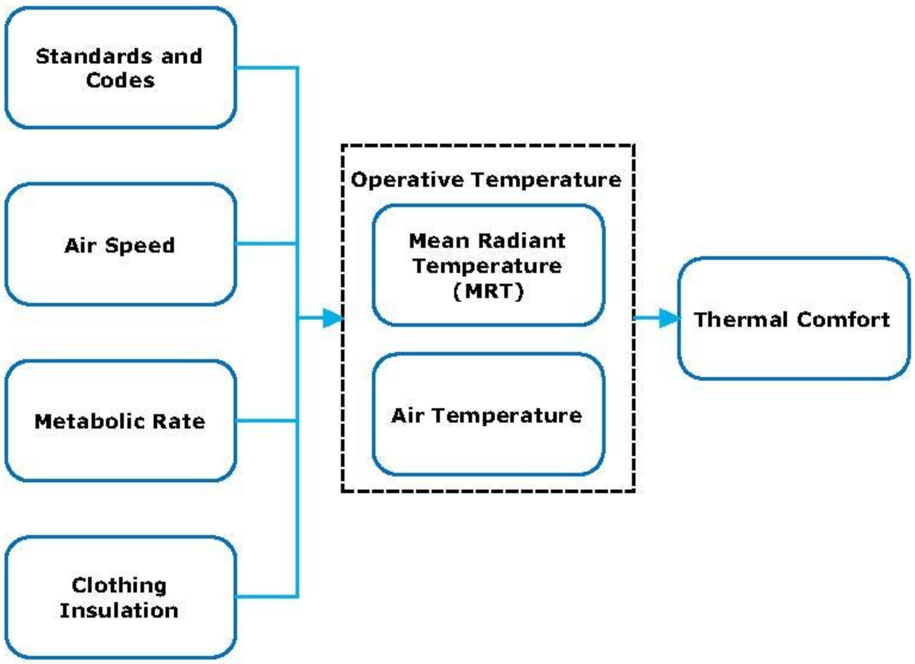


Figure 3.14. Variables affecting the operative temperature

3.1.2.3.5 Air temperature

Air temperature as defined in ANSI/ASHRAE 55 (2004) is the average temperature of the air surrounding the occupant. This average is the numerical average of the air temperature at the ankle level (4 inches), the waist level (24 inches), and the head level (43 inches) for seated occupants. For standing occupants they are at 4 inches, 43 inches and 67 inches respectively.

Air temperature, at the previously specified locations, is the three-minute average with at least 18 equally spaced points in time (ANSI/ASHRAE 55 2004). This temporal average could be measured directly using adequate thermostat equipment.

3.1.2.3.6 Mean Radiant Temperature (MRT)

When designing and using RC systems, the mean radiant temperature (t_r) is the key variable in the thermal calculations of the human body. MRT as defined in ANSI/ASHRAE 55 (2004) is the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space. It is a single value for the entire body and may be considered a spatial average of the temperature of surfaces surrounding the occupant weighted by their view factors with respect to the occupant (ANSI/ASHRAE 55 2004). MRT is the average of a three-minute average with at least 18 equally spaced points in time.

3.1.2.3.7 MRT calculation

MRT is a calculated value and cannot be measured directly like air temperature. However, measuring the MRT is a difficult procedure, and there are many methods to calculate its value.

Olesen et al. (1989) mentioned three methods of calculating and measuring MRT. a) The weighted mean value of the plane radiant temperature of the surrounding walls and surfaces and their position with respect to the occupant. b) Using a spherical-shaped globe sensor to simulate a seated person. c) Using an ellipsoid-shaped globe sensor to simulate a standing person. Watson and Chapman (2002) described another method based on the radiant intensity balance at a particular point in the space. Each one of these methods has its own limitations and advantages.

The simplest method, with acceptable accuracy, is by using a black globe thermometer, in addition to air temperature, and air velocity. Thus, MRT is calculated by the Eq. 3.6:

$$\bar{t}_r = [(t_g + 459.67)^4 + (4.74 * 10^7\, V_a^{0.6})\,(t_g - t_a) / \varepsilon\, D^{0.4}]^{1/4} - 459.67 \qquad \text{Eq. (3.6)}$$

Where:
$\bar{t}_r$ *: mean radiant temperature, °F*
t_g*:globe temperature, °F*
V_a*:air velocity, fpm*
t_a*: air temperature, °F*
D: globe diameter, ft
ε: emissivity (0.95 for black globe)

"The accuracy of the MRT determined in this way varies considerably depending on the type of environment and the accuracy of the individual measurements. Because the MRT is defined with respect to the human body, the shape of the sensor is also a factor" (ASHRAE 2009).

MRT can be also calculated based on the measured temperature of surrounding walls and surfaces and their position with respect to the person using Eq. 3.7:

$$\bar{T}_r^4 = T_1^4 F_{p\text{-}1} + T_2^4 F_{p\text{-}2} + \ldots + T_N^4 F_{p\text{-}N} \quad \text{Eq. (3.7)}$$

Where:
$\bar{T}_r$ *: mean radiant temperature, °R*
T_N *: surface temperature of surface N, °R*
$F_{p\text{-}N}$ *: angle factor between a person and surface N*

MRT can be also calculated from the plane radiant temperature (t_{pr}) in six directions and for the projected area factors of a person in the same six directions using equations 3.8 and 3.9:

For standing person:

$$\bar{t}_r = \{0.08[t_{pr}\,(\text{up}) + t_{pr}\,(\text{down})] + 0.23[t_{pr}\,(\text{right}) + t_{pr}\,(\text{left})] + 0.35[t_{pr}\,(\text{front}) + t_{pr}\,(\text{back})]\} \,/\, [2(0.08 + 0.23 + 0.35)] \quad \text{Eq. (3.8)}$$

For seated person:

$$\bar{t}_r = \{0.18[t_{pr}\,(\text{up}) + t_{pr}\,(\text{down})] + 0.22[t_{pr}\,(\text{right}) + t_{pr}\,(\text{left})] + 0.30[t_{pr}\,(\text{front}) + t_{pr}\,(\text{back})]\} \,/\, [2(0.18 + 0.22 + 0.30)] \quad \text{Eq. (3.9)}$$

Plane radiant temperature as defined in ANSI/ASHRAE 55-2004 is the uniform temperature of an enclosure in which the incident radiant flux on one side of a small plane element is the same as in the existing environment.

In the previouse two methods, the angle factor should be determined, which is not an easy task. However, Figure 3.15 shows charts developed by Fanger in 1982 and published (ASHRAE 2009) which may be used to determine the angle factor.

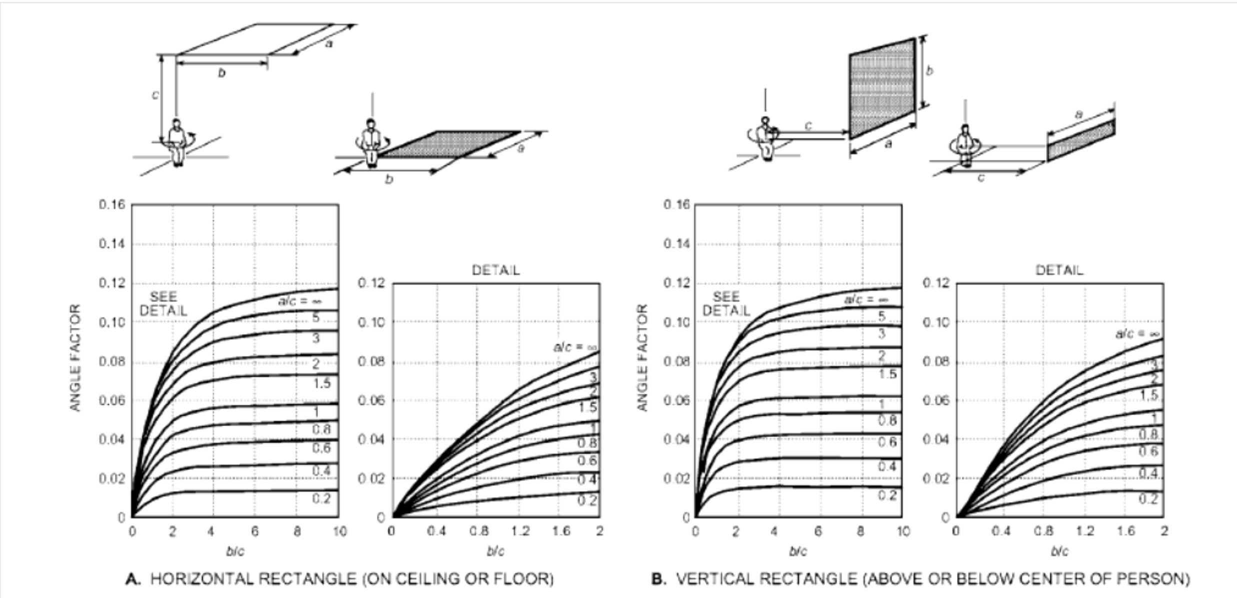


Figure 3.15. Mean value of angle factor between seated person and horizontal or vertical rectangle when person is rotated around the vertical axis
Source: (ASHRAE 2009)

Use of either of the previous methods has limits. For example, equation 3.7 assumes that the surface materials have high emittance and are considered to be black. This assumption does not take into account low-E glass where its published emissivity is less than 0.1. Another shortcoming in these methods is they do not consider radiant transmission through a window as the walls' surface temperatures are used as the boundary conditions (Watson and Chapman 2002).

Watson and Chapman (2002) mentioned a different method to derive MRT based on the energy intensity calculations as shown in the Eq. 3.10:

$$\bar{T}_r = \left[\sum I^i A^j_p w^j \,/\, f_{eff} A_D \sigma \right]^{1/4} \qquad \text{Eq. (3.10)}$$

Where:
$\bar{T}_r$ *: mean radiant temperature, °R*
I^i *: The energy intensity coming from a given direction, w/m²*
A^j_p*: Projected area in the given direction, m²*
W^j *: the quadrature weighting function for the given direction*
f_{eff} *: effective radiation area, m²*
A_D*: DuBois area, 1.82 m² (19.6 ft²)*

This method does not make any assumptions regarding the wall surface properties, and there is no need to calculate the angle factor when using this method.

In conclusion, MRT plays a major role in determining the space operative temperature. MRT depends on the radiant energy exchange in the space, therefore the space geometry, materials properties, and window placement play important roles in the MRT calculation. Also, the occupant location and orientation are important factors affecting MRT calculation. Figure 3.16 summarizes the previous discussion:

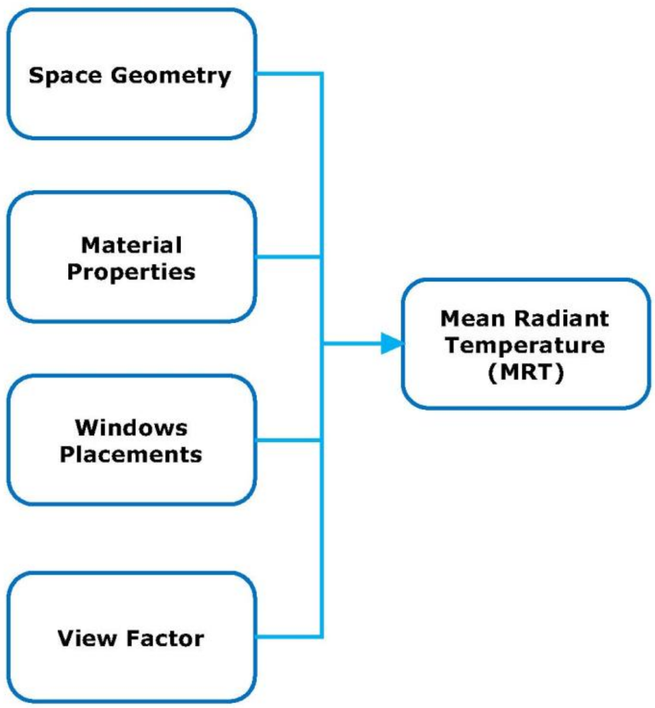


Figure 3.16. Variables affecting the MRT value

Andreas Limberg (personal communication, April 15, 2011) and Fred Bauman (personal communication, April 15, 2011) mentioned that in real situations, it is too complicated to design the RC system with specific surface temperature to maintain a certain MRT in the space. The process of calculating MRT is very complicated and need sophisticated and very expensive simulation software which is not typically used in average building projects. However, when installing RC systems in a space the MRT will be closer to the thermal comfort zone when compared to spaces with conventional HVAC systems.

3.1.2.3.8 Air speed

The precise relationship between increased air speed and improved comfort has not been well established (ANSI/ASHRAE 55 2004). However, ASHRAE (2009) established a relationship between dissatisfaction and mean air velocity under three different air temperatures as shown in Figure 3.17.

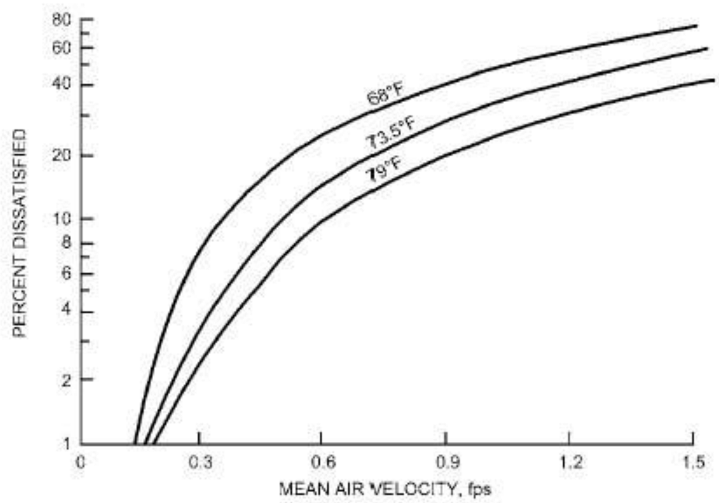


Figure 3.17. Percentage of people dissatisfied as function of mean air velocity
Source: (ASHRAE 2009)

However, RC systems do not provide air for ventilation nor do they take care of the space latent heat. Most air systems are designed to maintain air velocities at levels that avoid thermal discomfort situations such as draft.

ANSI/ASHRAE 55-2004 Standard indicates that the upper limit of the acceptable air temperature could be increased as shown in Figure 3.18, if occupants have the ability to control air speed. However, this figure applies to people wearing 0.5 - 0.7 clo. and engaged in activities with metabolic rates between 1.0 met and 1.3 met.

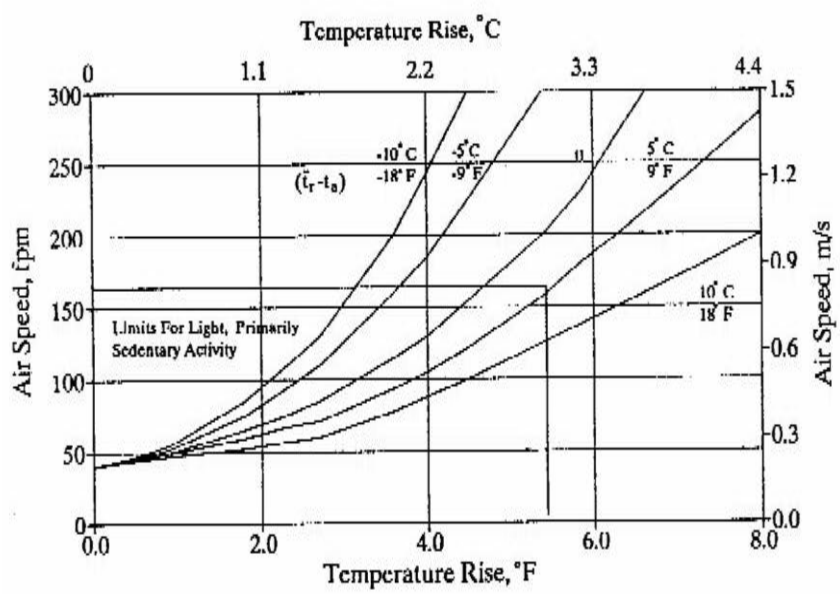


Figure 3.18. Air speed required to offset increased air and radiant temperatures
Source: (ANSI/ASHRAE 55 2004)

From Figure 3.18 it is important to notice that the elevated air speed is less effective when the MRT is low and the air temperature is high, while it is an effective strategy in the opposite situation. Also, the offset temperature is not to exceed 5.4 °F (3.0 °C) for people with metabolic rates less than 1.3 met and clothing insulation less than 0.5 clo (ANSI/ASHRAE 55 2004).

In conclusion, air speed has an effect on thermal comfort. Air speed may increase to offset increased radiant temperature and air temperature, but it is an ineffective strategy in the case of RC systems. Occupants' metabolic rate and clothing insulation are important to determine the air speed value in the space. The ventilation strategy is important for determining the air speed inside the conditioned space. Figure 3.19 summarizes the previous discussion:

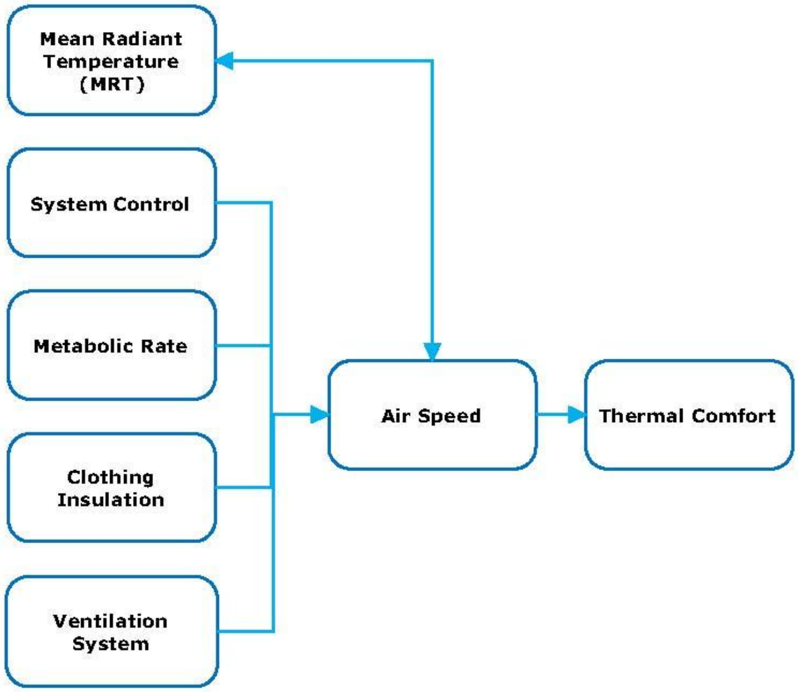


Figure 3.19. Variables affecting air speed inside the conditioned spaces

3.1.2.3.9 Humidity

According to ANSI/ASHRAE 55 (2004) the upper limit for the humidity ratio within the thermal comfort zones is 0.012 lb_{water} / lb_{dry_air} (kg_{water} / kg_{air}) which corresponds to a water vapor pressure of 0.277 psi (1.910 kPa) at standard pressure or a dew point temperature of 62.2 ˚F (16.8 °C). At the same time, the standard does not establish a lower limit for the humidity ratio but does mention that other non-thermal factors such as skin drying, static electricity, etc., may suggest lower limits for the humidity ratio.

High humidity tends to cause thermal discomfort, due to the feeling of the moisture itself and increased friction between clothing and skin. Therefore it is recommended that the RH does not exceed 60% during summer conditions (ASHRAE 2009).

Humidity control is a potentially limiting factor for RC systems which could in turn affect their cooling capacity. It is important to keep the cooling surfaces at all times above the dew-point temperature of the space to avoid condensation. For example, at an air temperature of 79 °F (26 °C) and relative humidity (RH) of 60% to 70% this corresponds to a dew point temperature (DPT) between 62.6 °F and 68 °F (17 °C and 20 °C). This means, in the case of using a chilled slab system, the floor surface temperature must always be higher than 68 °F (20 °C) (Olesen 1997).

Olesen (1997) recommended the surface temperature of chilled floors not be lower than 68 °F (20 °C) for sedentary or standing occupants as 66.2 °F (19 °C) is the lower allowable temperature according to ANSI/ASHRAE Standard 55 2004. He mentioned that it is possible in densely occupied spaces to lower the surface temperature to increase the cooling capacity of the system. Then he added: “the use of dehumidification in a room by an air-conditioning system or a simple dehumidifier will decrease the dew-point temperature and then increase the cooling capacity of a floor system”.

Adding to this, Dieckmann, Roth, and Brodrick (2004) mentioned that with a dedicated outdoor air system (DOAS), a system that efficiently supplies cool dry outdoor air where radiant ceiling cooling panels are used, and tight building envelopes, humidity issues can be managed and controlled. This suggests that humidity control is a design issue for RC systems and potentially a constraint for their application. This also suggests the characteristics of the building envelope must be part of a RC system design process.

Maintaining the chilled surface temperature above the dew point temperature (DPT) may affect the cooling capacity of the RC system especially in hot humid climatic zones. Two issues need to be considered for this point: the thermal inertia of the cooled surface and the time duration the surface temperature is under the DPT. In the case of the chilled slab, due to its high thermal inertia, the supply water can be under the DPT, which means a higher cooling capacity without risking the surface temperature being under the DPT. For ceiling panels systems, which have relatively low thermal inertia, the supply water temperature has to be always above the DPT.

However, as many response factors will be temporal, having the surface temperature below the DPT may not necessarily cause an immediate system failure due to condensation. Mumma (2001) showed that running a horizontal chilled surface, Radiant Cooling Ceiling Panel system, for 8.5 hours at 14˚F (8 °C) below the space DPT was not enough to cause a single drop to fall even though condensation happened on the surface. However, Mumma did not mention the RH of the space during the experiment. This experiment may suggest that there is some flexibility in controlling the surface temperature and it may not be a limiting factor under certain conditions. It could be argued that if condensation happens regularly in the ceiling panels, this could endanger the integrity of the ceiling panels' material as it may rot/rust/stain over time, or could lead to IAQ health problem due to mold and fungi formation.

Special attention should be given for spaces with natural ventilation, high infiltration rates, or frequent use of outside doors, as under these conditions there are greater chances for condensation to occur. Moreover, the interactions of these situations with the RC system implementation should be considered early in the design process.

In conclusion, RH has great influence on human thermal comfort which should be considered for human thermal sensation. In the case of RC systems, it is important to maintain cooled surfaces' temperature above the space's dew point all the time, which means controlling the RH inside the conditioned spaces.

The humidity level inside the space is related to the indoor air temperature, occupants metabolic rate, space envelope configuration, ventilation strategy, standards and codes, and the dehumidification system inside the space. Indoor RH may constrain the RC system surface temperature and thus limits the system cooling capacity.

If the RC system goes under the space's DPT condensation may start to form, but water dripping will take time to occur. This situation is not recommended as it may lead to problems related to IAQ or endanger the integrity of the RC system itself.

Sources of humidity, either external or internal to the space, have to be controlled and well considered when using RC systems. Humidity sources could be from outdoor humid air, occupants, and equipment. Figure 3.20 summarizes the previous discussion:

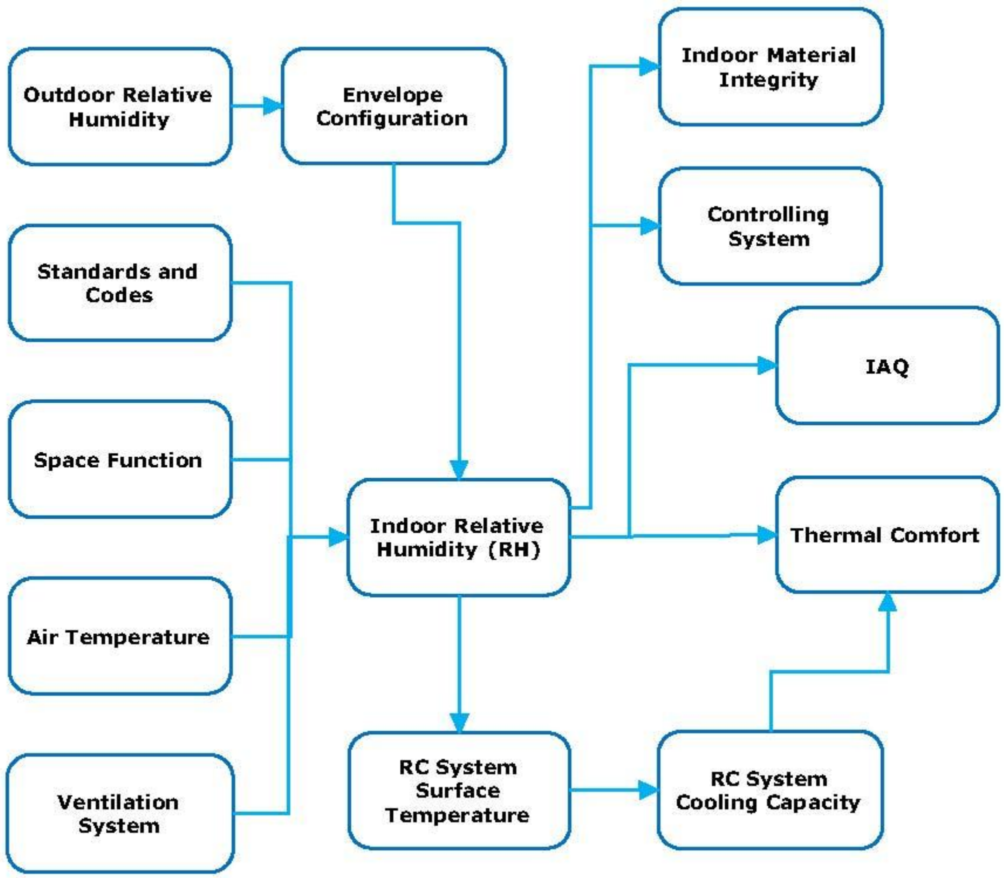


Figure 3.20. The humidity variable in spaces with RC system

3.1.2.3.10 Humidity control

Straube (2002) classified the sources of moisture in buildings into four categories as shown in Figure 3.21:

a) Liquid water; from rain, melting snow, and plumbing leaks.
b) Water vapor; from the exterior (infiltration, ventilation air, and makeup air) and from the indoor activities including human activities.
c) Liquid and vapor; from the soil around the building
d) Moisture and vapor built-in with the materials of construction or brought in with goods and people.

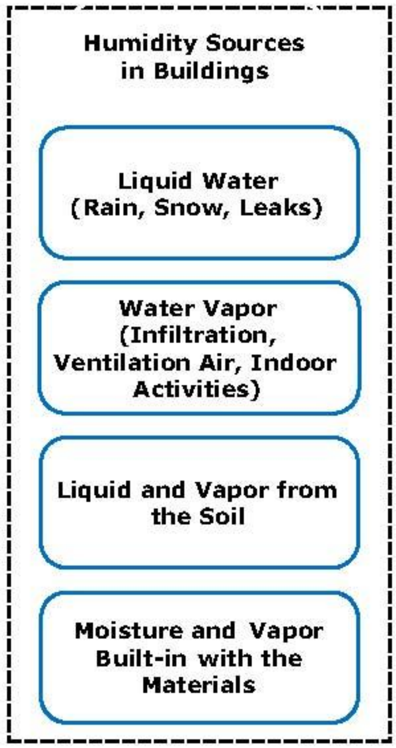


Figure 3.21. Common humidity sources in the built environment

In general moisture causes many problems in buildings. It is the most important factor in the building degradation process which may limit its useful life. Also, it could decrease the thermal resistance of the building and insulation materials. Other major problems are associated with the growth of molds, fungi, and dust mites which may cause danger and serious problems to the occupants (ASHRAE 2009).

Moisture control is a critical factor for successful use and implementation of RC systems. Humidity control will allow higher cooling capacity and avoid condensation on the systems' surfaces.

To avoid moisture accumulation in buildings, moisture entries into the building envelope should be minimized and moisture generated within the space should be removed. Better understanding of moisture sources and their mechanisms for movement will produce better, healthier, and more economical buildings and conditioning systems.

Straube (2002) mentioned four conditions to be satisfied to cause moisture movements. "A moisture source must be available, there must be a route or means for this moisture to travel, there must be some driving force to cause moisture movement, and the material(s) involved must be susceptible to moisture damage". Controlling any of these cause will minimize the moisture movement into the conditioned space.

Moisture sources could be in the form of liquid or vapor. Sources could be from precipitation, plumbing leaks, interior activities, adjoining soil, and built-in with the material of construction or people entering the building. The vapor transportation mechanisms could be due to vapor diffusion, vapor convection, liquid water capillarity, or liquid gravity flow.

Strategies to control moisture accumulation are by either minimizing its entry to the building envelope or by removing it from the building envelope. When the transportation mechanism is identified, counter procedures could take place such as constructing a rain screen wall, installing airflow retarders and/or water vapor retarders.

Other options to prevent moisture intrusion include designing the whole building or part of it to be under positive pressure relative to the ambient. Designing and constructing with moisture tolerance is another effective strategy for humidity control. Variables such as construction materials, climate conditions, cost, and energy consumption play important roles in determining the best strategy to adapt.

As it is almost impossible to prevent moisture migration in most buildings, "buildings construction should include drainage, ventilation, removal by capillary suction, or other provisions to carry away unwanted water" (ASHRAE 2009).

3.1.2.4 Conditions of local thermal discomfort

Local thermal discomfort is the situation where the person may feel thermally neutral as a whole but still feel uncomfortable if one or more parts of the body are too warm or too cold (ASHRAE 2009). ANSA/ASHRAE 55 (2004) identifies four conditions for local thermal discomfort; asymmetric or nonuniform thermal radiation, draft, vertical air temperature difference, and warm or cold floors as shown in Figure 3.22. The conditions for local thermal discomfort are quantifiable and predictable as explained in the following sections. Also, the majority of people are insensitive to these conditions in their lower limits.

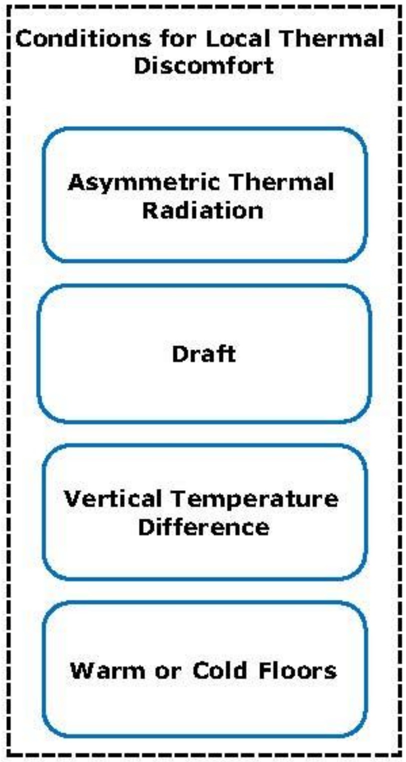


Figure 3.22. Variable affecting the local thermal discomfort

3.1.2.4.1 Asymmetric or nonuniform thermal radiation

ASHRAE (2009) defines radiant asymmetry as " the difference in radiant temperatures seen by a small flat element looking in opposite directions". The percentage of people expressing discomfort due to asymmetric radiation is established as seen in Figure 3.23.

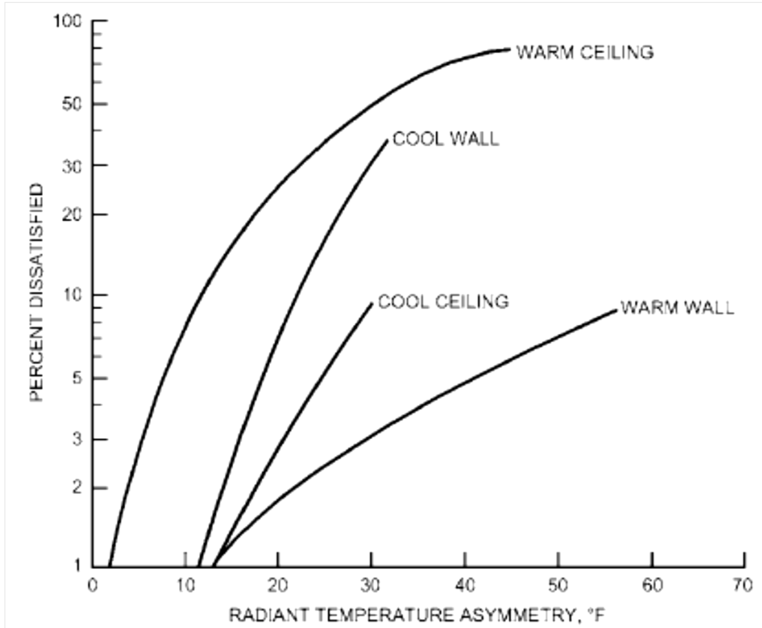


Figure 3.23. Percentage of people expressing discomfort due to asymmetric radiation Source: (ASHRAE 2009)

In the building environment, the main cause for this condition is being exposed to a hot or cold surface and to direct sunlight. The previous figure shows that people are more sensitive to asymmetric radiation caused by cold vertical surfaces than that caused by a cold ceiling.

However, ANSA/ASHRAE 55 (2004) set the limits for the allowable radiant temperature asymmetry as shown in Table 3.3.

Table 3.3. Allowable radiant temperature asymmetry Source: (ANSI/ASHRAE 55 2004)

Radiant Temperature Asymmetry °F			
Warm Ceiling	Cool Wall	Cool Ceiling	Warm Wall
< 9.0	<18.0	<25.2	<41.4

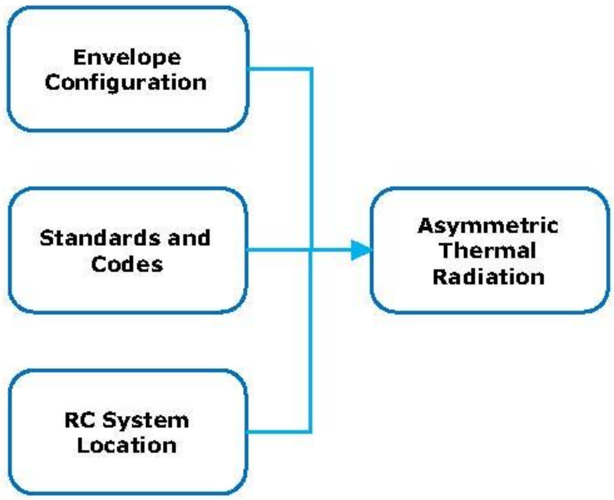


Figure 3.24. Variables affecting asymmetric thermal radiation

3.1.2.4.2 Draft

Draft, which is the unwanted local cooling of the human body cased by air movement (ASHRAE 2009), depends on many factors. Air speed, air temperature, turbulence intensity, human activity, and clothing are factors which determine the human sensitivity to draft. Figure 3.25 shows the limits for allowable mean air speed as a function of air temperature and turbulence intensity.

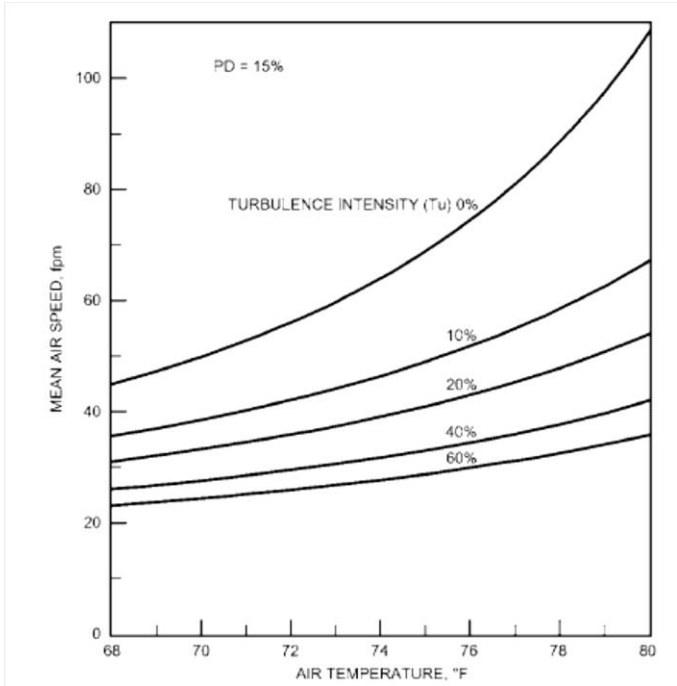


Figure 3.25. Draft conditions dissatisfying 15% of population (PD =15%)
Source: (ASHRAE 2009)

“Sensitivity to draft is greatest where the skin is not covered by clothing, especially the head region and the leg region” (ASHRAE 2009). However, when using RC systems where air is not the primary source of cooling such as RC systems, the draft effect is related to the supplementary ventilation system if used.

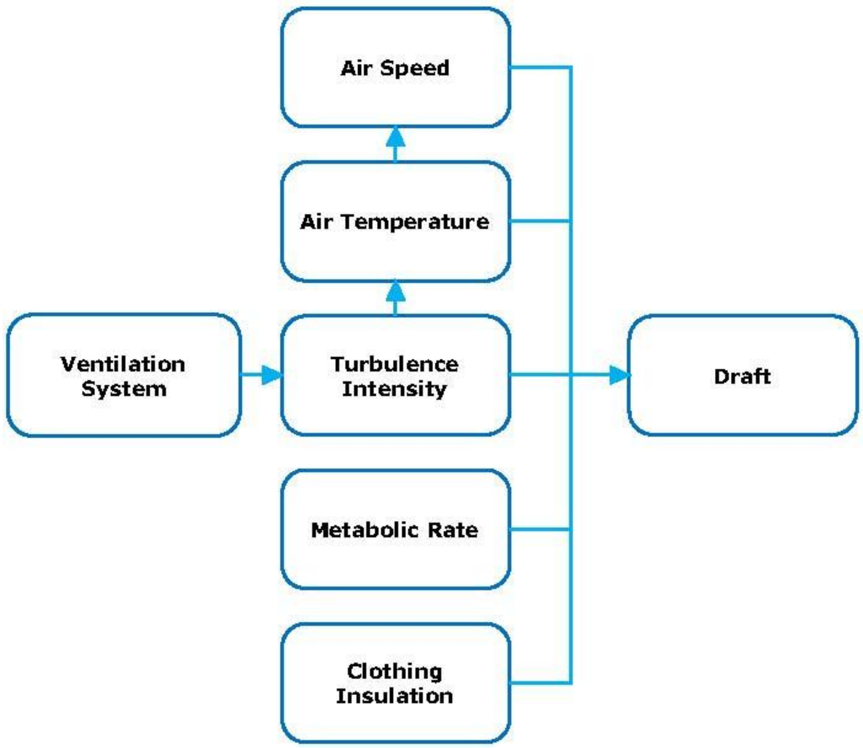


Figure 3.26. Variables affecting the draft sensation

3.1.2.4.3 Vertical air temperature difference

If the air temperature at the head level is significantly warmer than air temperature at the ankle level (thermal stratification), this will cause local thermal discomfort for the occupants. Thermal stratification in the opposite direction rarely happens and is not critical for occupants who can tolerate much greater differences (ASHRAE 2009).

Figure 3.27 shows the percentage of seated people dissatisfied as a function of air temperature difference between head and ankles. ANSA/ASHRAE 55-2004 sets the maximum allowable vertical air temperature difference between head and ankles at 5.4 °F.

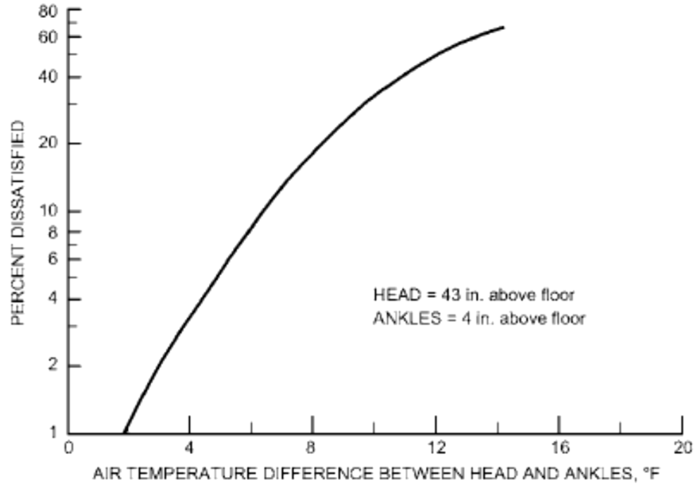


Figure 3.27. Percentage of seated people dissatisfied as function of air temperature difference between head and ankles
Source: (ASHRAE 2009)

Olesen (2008) mentioned that the use of chilled slab system will not cause any local discomfort because of the vertical air temperature difference. Tian and Love (2006) explained in a field study experiment that the vertical air temperature difference when using chilled slab system was lower than 0.5 K.

3.1.2.4.4 Warm or cold floors

Floor surface temperature is an important factor in the thermal comfort equation especially when using chilled slab systems. Occupants have direct contact with the floor and can feel its temperature directly and that could affect their thermal comfort sensation. Also, floor temperature has significant impact on the room's mean radiant temperature.

In the situations where occupants have bare feet, the floor material and floor temperature are important for local thermal comfort. However, to minimize the desire for higher ambient temperature, flooring materials with a low contact coefficient could be used. Figure 3.28 shows the percentage of people, wearing normal indoor footwear, dissatisfied as a function of floor temperature.

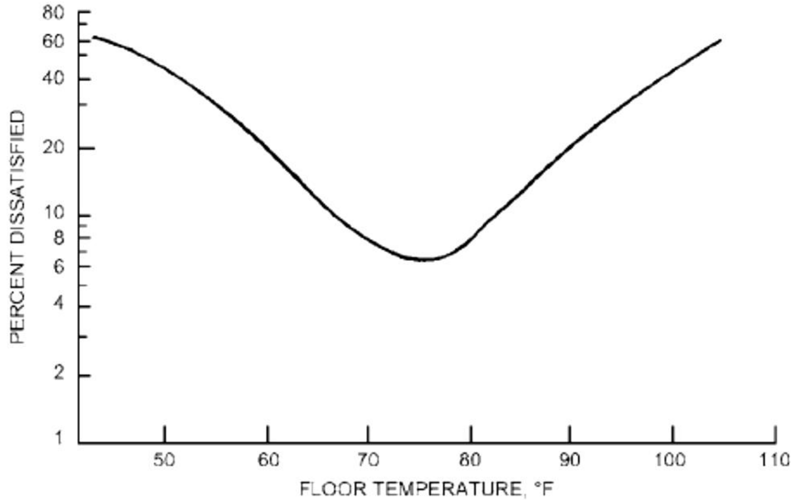


Figure 3.28. Percentage of people dissatisfied as function of floor temperature
Source: (ASHRAE 2009)

ANSA/ASHRAE 55 (2004) sets the allowable range of surface temperature of the floor to be between 66.2 °F and 84.2 °F. However, Olesen (2004) found that the optimal floor temperature is 77 °F for sedentary and 73.5 °F for standing and walking persons wearing normal indoor footwear. At these optimal temperatures 6% of the occupants felt warm or cold discomfort in the feet (ASHRAE 2009).

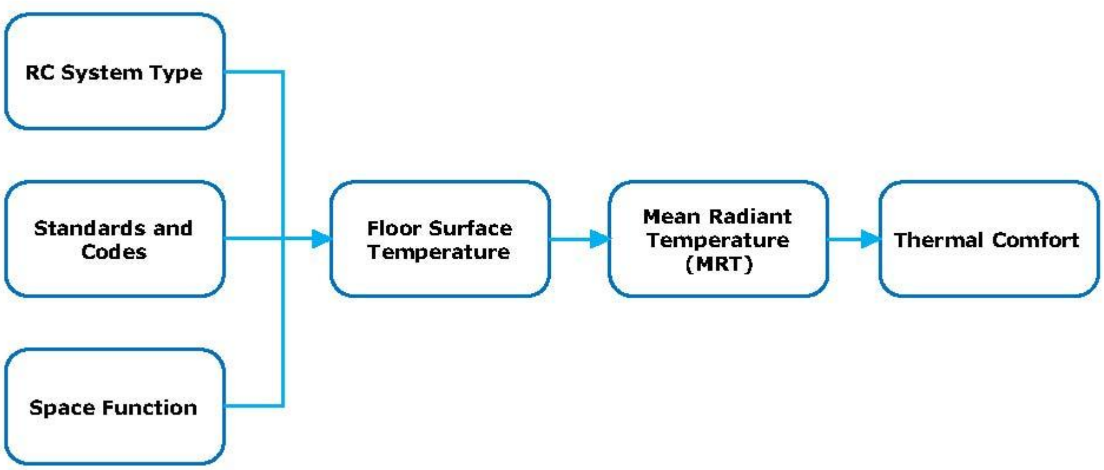


Figure 3.29. Variables affecting the floor surface temperature

3.1.2.5 Indoor Air Quality (IAQ)

According to ANSI/ASHRAE 62.1 (2007), RH in occupied spaces should be limited to 65% or less. To maintain this condition dehumidification systems/strategies to be installed in mechanically cooled spaces

Although there is no specific definition for IAQ, there is a general agreement that IAQ is: the quality of indoor air which is characterized by physical factors (ambient temperature and humidity), mechanical factors (air speed, ventilation rate, and distribution), and chemical factors (mass pollutants and energy pollutants from inside and outside) (Rush 1986) as shown in Figure 3.30. ANSI/ASHRAE 62.1 (2007) defines acceptable IAQ as the: "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction".

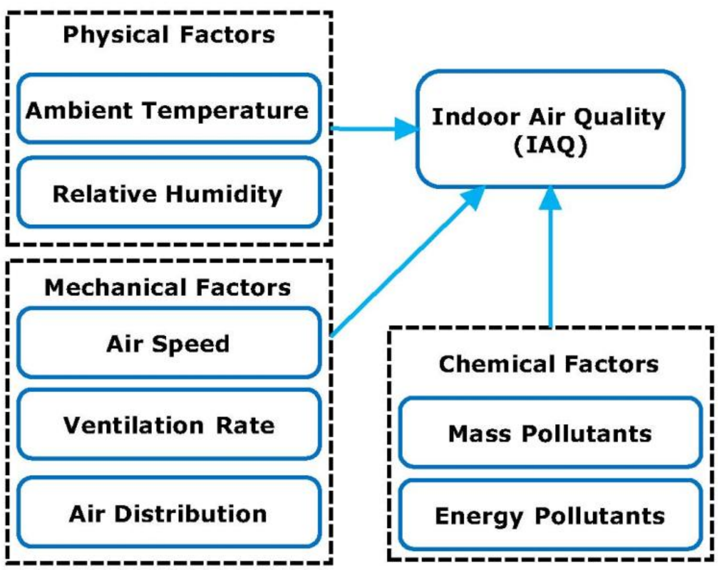


Figure 3.30. Variables affecting the IAQ

There are close relationships between IAQ and occupant's health and wellbeing. Seltzer (1996) mentioned that "the likelihood that an individual will become ill from the presence of a contaminant [IAQ contaminants] depends upon factors such as the individual's sensitivity to that contaminant, the contaminant concentration, the current state of their psychological and physical health, and the duration and frequency of exposure". Since people spend about 80% to 95% of their time indoors, indoor air contamination levels at any significant level could create serious health problems. “Indoor air pollutants have the potential to cause transient morbidity, disability, disease, and even death in extreme cases” (B. Berglund et al. 1992).

Another study by Fisk and Rosenfeld (1998) claimed that: “the annual cost of indoor air quality related problems [is] at $100 billion. These costs are incurred due to problems such as SBS [Sick Building Syndrome], BRI [Building Related Illness], absenteeism, and operation and maintenance cost of problematic buildings”. In a review of literature conducted by O. Seppänen and W. J. Fisk (2002) they found that there was an increase in SBS symptoms associated with mechanically ventilated buildings, although they could not conclude the reasons for such an increase.

IAQ does not only affect occupants’ health and wellbeing, it also has an effect on their performance and productivity. Figure 3.31 from the ‘*Indoor Air Quality Scientific Findings Resource Bank*’ website by Lawrence Berkeley National Laboratory (2008) shows the predicted performance of office work at various ventilation rates.

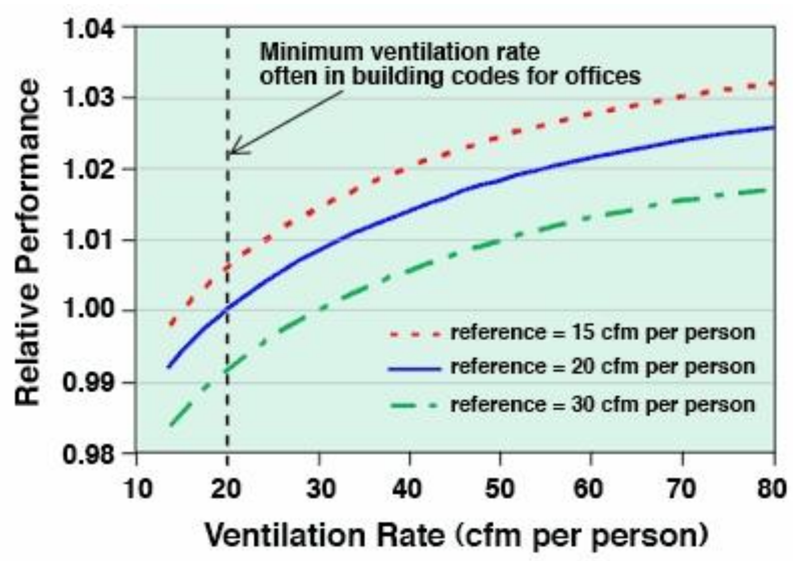


Figure 3.31. Predicted performance of office work at various ventilation rates relative to performance at the indicated reference ventilation rates
Source: (Lawrence Berkeley National Laboratory 2008)

As Figure 3.31 suggests, tripling the ventilation rate would increase the relative performance about 2%. It could be argued that the increase in energy consumption associated with this increase in the ventilation rate is unjustified from an economical point of view.

Ventilation systems or techniques could be considered as the tools to achieve the desired IAQ situation. Ventilation systems are to assure three major goals: minimizing outdoor pollution intrusion, providing and distributing fresh air to the interior, and flushing the polluted indoor air to the outdoors (Rush 1986). Understanding the mechanisms to achieve the previously mentioned goals is important to provide good IAQ environment for the occupants.

Figure 3.32. The ventilation system role in IAQ

According to ANSI/ASHRAE 62.1-2007, spaces intended for human occupancy have to be ventilated naturally or mechanically to provide acceptable indoor air quality (IAQ). This means RC systems must be supplemented with a ventilation air system. This also means separating the cooling task from the ventilation task. Air could be introduced to spaces naturally or mechanically. Natural ventilation, where applicable, could maintain acceptable IAQ and take care of the latent cooling load. Mechanical ventilation may assure, in properly designed and operated systems, constant IAQ within the conditioned spaces.

Conventional HVAC systems could take care of the sensible and latent loads of the space in addition to providing mechanical ventilation. RC systems only remove sensible cooling loads, where latent loads removal and ventilation have to be provided by additional systems to assure good IAQ and an energy efficient air exchange rate (Behne 1999). Thus, when considering RC, the ventilation strategy needed to provide an acceptable IAQ is required by the relevant codes should be considered as well.

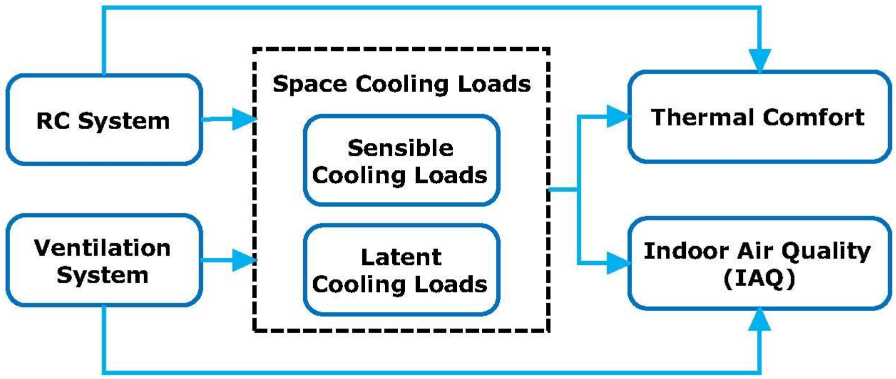


Figure 3.33. RC system and ventilation system are working together affecting the thermal and IAQ environments of the conditioned space

Separating the cooling system (RC systems) from the ventilation system may have the following benefits:

a) Based on a study of office buildings with conventional HVAC systems, Stetiu (1998) mentioned that "at the time of peak cooling load, only 10%-20% of the supply air is fresh air, and only this small fraction of the supply air is necessary to ventilate buildings to maintain acceptable indoor air quality".
b) For spaces with RC systems and dedicated ventilation systems that the duct-cross sectional dimensions become much smaller than those used in forced-air systems which make the vertical plenum space savings possible, and smaller vertical shafts (Conroy and Mumma 2001).
c) Supply and return fan size are also significantly reduced (Conroy and Mumma 2001).

In conclusion, there are different strategies to introduce air to the space; each of them has a direct effect on the IAQ and, thus, occupants' comfort. The relationship between the major air distribution patterns and the RC implementation on the space is explored and mapped in the framework. Major air distribution patterns which may consider as an architectural decisions are: displacement flow, conventional mixing, and natural ventilation.

3.1.2.5.1 Ventilation systems

Ventilation systems are mainly to maintain acceptable IAQ conditions. Also, they affect the indoor thermal environment by supplying cool air to the conditioned spaces as in the conventional HVAC systems. Design a combined RC system and a ventilation system that would satisfy the thermal comfort and the IAQ requirements may be challenging. There are complex interactions between both systems, and following the design guidelines for the RC system and the ventilation system as independent systems is not appropriate when having them both in the same space (Novoselac and Srebric 2002).

Several studies, experimental and numerical (computer modeling), have been done to explain the complex interactions between both systems. However, due to the variety of ventilation system types and RC system types and configurations, these studies a) are limited by the design parameters of each case and their results cannot be generalized, and b) do not cover all possible combinations. This section summarizes the findings of these studies.

3.1.2.5.1.1 RCCP system and displacement ventilation (DV) system

Displacement ventilation (DV) system is a ventilation system that supplies conditioned air with low air velocity directly to the occupied zone, then air is extracted typically at the ceiling levels causing temperature and contaminants stratification (Hodder et al. 1998). The temperature difference between the supply air and the conditioned room air should be relatively small to avoid thermal local discomfort caused by temperature stratification. Also, increased air flow would case the stratified conditions into mixing ventilation conditions. These constraints may limit the DV system cooling capacity and call for an additional cooling system such as RCCP system (Loveday et al. 2002). Properly designed RC and DV systems combination would create an enhanced IAQ and thermal environments compared to other systems such as VAV systems (Novoselac and Srebric 2002). The following points summarize the main points related to the combined RCCP and DV systems.

For the combined systems, the existence of the vertical temperature gradient indicates temperature and contaminants vertical stratification. The temperature gradient must be small to avoid local thermal discomfort. This vertical gradient depends on the ratio of the cooling loads removed by the RCCP system to the cooling loads removed by the DV system. If the cooling load portion removed by the RCCP system is significantly larger than what is removed by the DV system, then the stratified air is interrupted, due to the downward airflow from the RCCP, causing relatively uniform temperature and contaminant distribution. Whereas, if the DV remove a larger portion of the total cooling loads, that would result a better IAQ environment. The uniform temperature distribution provides better thermal comfort but not a better air quality.

However, temperature gradient will create better IAQ environment but should not cause local thermal discomfort situations (Novoselac and Srebric 2002; Alamdari et al. 1998).

ANSA/ASHRAE 55 (2004) sets the maximum allowable vertical air temperature difference between head and ankles at 5.4 °F as explained in section 3.1.2.4.3. Behne (1999) suggested that the DV to remove at least 20-25% of the total cooling loads to achieved a good IAQ and thermal environment conditions as shown in Figure 3.34.

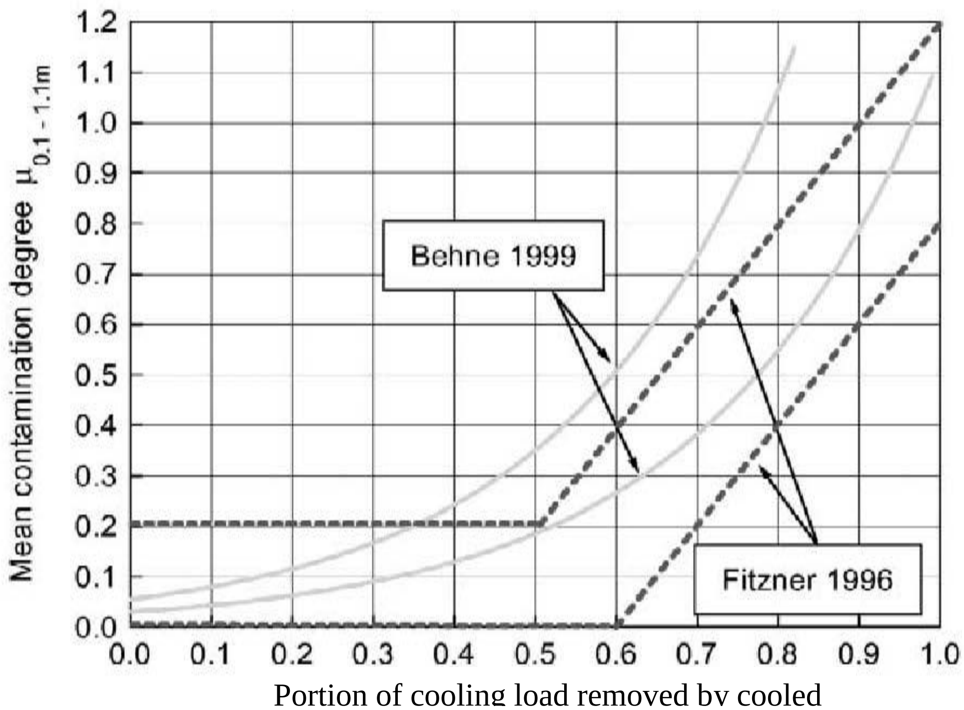


Figure 3.34 The cooling load removed by RCCP system vs. the mean contamination degree by two different studies.
Source:(Novoselac and Srebric 2002)

Behne (1999) explained that in office buildings if the displacement ventilation removes 20-25% of the total space cooling loads, then good results for thermal comfort and IAQ can be achieved. He added that increasing the cooling capacity of the dispalcemnt ventilation system could interrput the IAQ environment and change it as in the mix ventilation system. Mix ventilation system with RCCP would creat uniform pollutatnt distribution and will not involove any problems with thermal comfort if the space cooling loads does not exceed 32 Btu/hr•ft² (Behne 1999). Behne recomedded to cover the whole ceiling with RCCP system, or to distribute them regurarly, or to arrange the cooled panels close to the displacemnet ventilation system inlets for better thermal comfort and air quality in the conditioned space.

Novoselac and Srebric (2002) showed in a numerical study for a conference room with combined RCCP and DV systems, that the temperature gradient and the IAQ at the breathing zone are almost identical when the ceiling height is varied from 8 to 16 feet. They also found that the RCCP removes the same cooling loads regardless the ceiling height within the previous range. They also showed that even the vertical average RH is almost constant, the RH profile was low at the occupied zone and high at near the RCCP system. This suggests that RH should be measured at the breathing level for occupants comfort and at the ceiling level to prevent possible condensation.

Novoselac and Srebric (2002) suggested different operation strategies for better thermal comfort, IAQ, energy consumption, and prevention from condensation, these strategies include the following:

a) Running the combined systems with constant airflow and fixed air temperature from the DV system, and variable surface temperature for RCCP system.
b) To change the RCCP system surface temperature, change the water flow variable with constant temperature rather than changing the water flow temperature with constant flow.
c) The risk of condensation is present during the system startup after nights and weekends, as the humidity level is high due to infiltration. An early startup time for the DV system and gradual startup for the RCCP system may eliminate this possible risk.
d) As suggest by many researchers, to keep the RCCP surface temperature at least 1-2 °F above the room dew point temperature.

3.1.2.5.1.2 RCCP system and Dedicated Outdoor Air System (DOAS)

The concept of the DOAS is to separate the ventilation system from the cooling system. DOAS will provide 100 % outdoor air for ventilation and take care of the space latent cooling loads while another system will handle the space sensible loads. Figure 3.35 explains the DOAS verses a conventional all-air system.

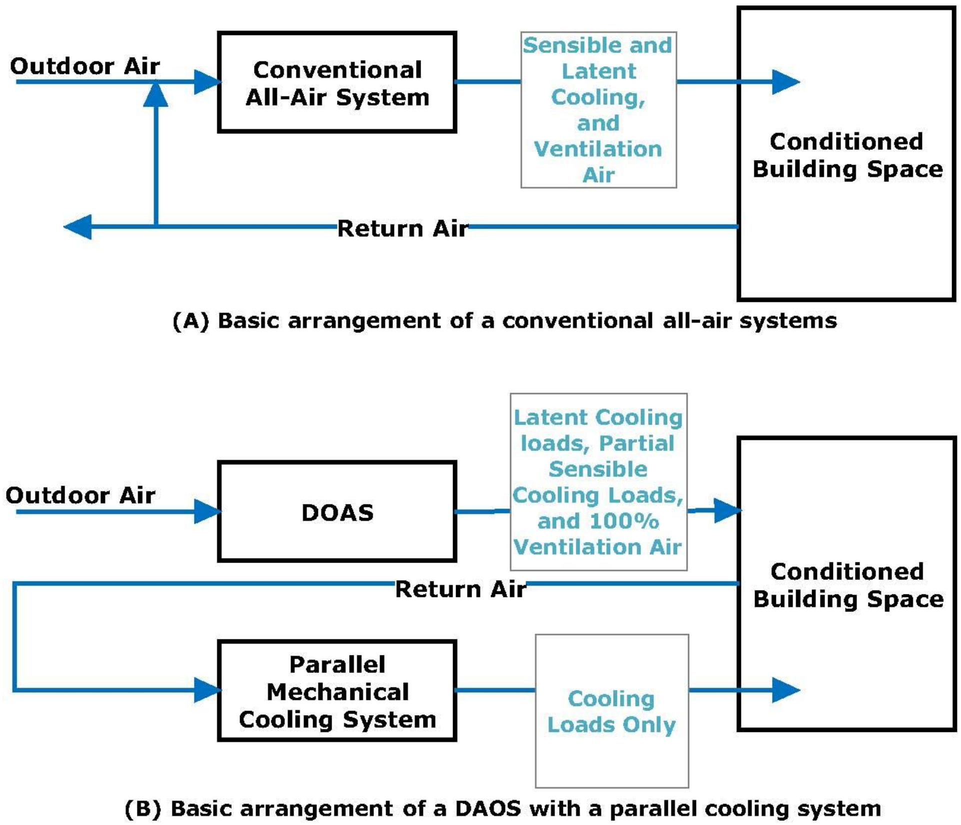


Figure 3.35 DOAS configuration versus conventional HVAC all-air system

When considering RC systems, DOAS seems to have advantages. For this system, only the required outdoor air is delivered to the conditioned space, where it can be controlled in terms of relative humidity and temperature. Coupling a DOAS with a RC system can improve the indoor air quality (IAQ), because the use of 100% outdoor air for ventilation purposes may better control humidity as "the primary source of building humidity in most climate areas is fresh outdoor ventilation air" (Madison Gas and Electric 2009).

The combination of a DOAS and a RCCP, shown in Figure 3.36, demonstrates how both systems could work together. The DOAS provides the required fresh air for ventilation and will satisfy the latent cooling loads of the space, while the RCCP removes the sensible heat from the space. However, in this configuration the DOAS is designed to work in both the summer and winter. The preheat coil is used in the winter to first warm up the outdoor air, which is necessary in many cold climates to avoid frosting of components such as an energy wheel. The enthalpy wheel brings the outdoor air humidity closer to the humidity of the conditioned exhaust air. In the summer the cooling coil cools and dehumidifies the air to the desired levels. The sensible wheel can be used to adjust the dry-bulb temperature of the air entering the conditioned space.

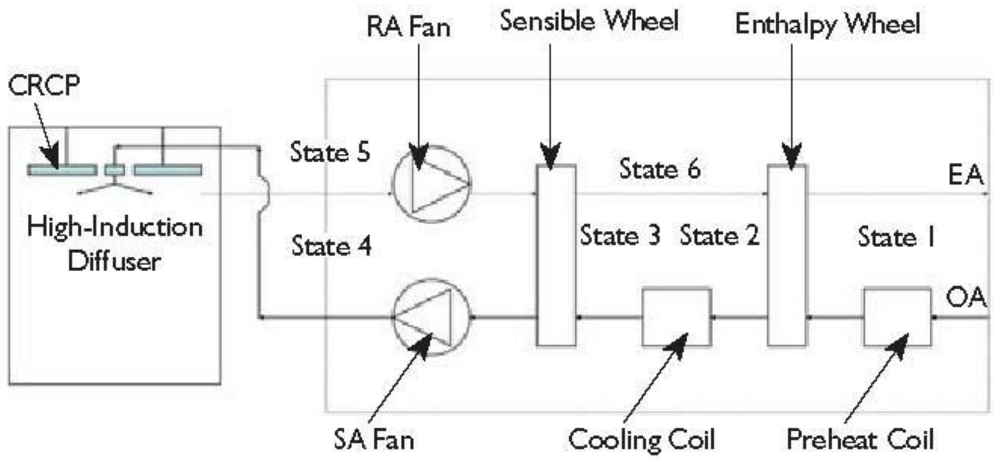


Figure 3.36. Typical DOAS and RCCP configuration
Source: (Jeong and Mumma 2006)

The air flow rate with the DOAS is about 20% of what needed in conventional HVAC systems. Mumma (2001) recommended to introduce the air into the conditioned space using high-aspiration diffusers so the occupants do not feel stagnant, and that would increase the RCCP system heat removal by around 15%. Also, Mumma (2001) recommended in DOAS and RCCP combination to introduce the air at constant volume with low temperature via ceiling diffusers to increase the heat removal by 15%, and for thermal comfort and IAQ issues.

In conclusion, beside the previously mentioned systems combinations, RC system can be installed with any ventilation system type as long as both systems are well designed and configured. However, the previous sections suggested using a simulation tool to explore the interaction points between both systems and then design accordingly. The following examples show different systems combinations:

a) Chilled slab along with displacement ventilation system was used in Bangkok international airport, Bangkok.
b) Chilled slab with active ceiling sides along with displacement ventilation system was used in Klarchek Information Commons, Loyola University, Chicago.

c) RCCP system along with overhead DOAS distribution system was used in an educational building within Penn State campus, Pennsylvania.
d) Chilled slab system with active ceiling sides was used in David Brower Center, Berkeley.

3.1.2.6 Acoustical performance

It is difficult to find a definition for acoustical comfort as the desired acoustical quality may differ significantly from one space to another. For example, when the main purpose in a hall is musical performance then the music must be dispersed to all locations as uniformly as possible, while the office environment, on the other hand, usually requires privacy for conversation and concentration. However, there are *acceptable* standards for noise levels in different areas. The International Organization for Standardization (ISO) developed the Noise Rating Curves (NRC) to determine the acceptable indoor environment for hearing preservation, speech communication and annoyance. In the U.S. it is more common to use the Noise Criterion (NC) for rating indoor noise coming from different sources. For example, the recommended NC level for classrooms is 25-35 which is equivalent to sound level of 35-40 dBA (Egan 1988).

Acoustical design and comfort can be achieved by finding a balance between the demands for communication, the need for privacy, and design for quietness. In general, “people prefer to work in quiet environments but not totally free of sound. People use sound for orientation, awareness, and masking to provide speech privacy” (Reffat and Harkness 2001).

According to Rush (1986), the acoustical quality depends on the control of three factors: sound sources, sound paths, and sound receivers. When designing for acoustical comfort, there are several factors to consider. Some of them are acoustical such as sound level, frequency, duration, fluctuations in sound level, material Noise Reduction Coefficient (NRC), etc., and others are nonacoustical such as necessity of the noise, listener’s personality, total area of glazed windows, ceiling, and floor materials, etc. (Reffat and Harkness 2001; Rush 1986). From the previous, it could be concluded that designing for acoustic comfort may interfere with other design strategies such as daylighting, natural ventilation and fire safety.

On the other hand noise, which is unwanted sound, comes from three different sources: noise coming from outside, noise from adjacent spaces, and from the lack of sound control in the space itself. Studies have shown that lack of noise control, mainly in indoor spaces, can lead to occupant dissatisfaction and serious health problems (DiNardi 2003; Kibert 2008).

Research results by Evans and Stecker (2004) found that people who are exposed to different sources of noise, regardless of its level, have less motivation to complete a certain task. Research by KL Jensen, Arens, and Zagreus (2005) showed that a poor acoustical environment interferes with worker performance in an office environment. A study by Vermeer and Passchier (2000) showed that exposure to noise can cause serious health risk such as "hearing impairment, hypertension and ischemic heart disease, annoyance, sleep disturbance, and decreased school performance". Zhisheng et al. (2007) reported that in institutional facilities studies showed that children's brains grow 20% more slowly in noisy environments than in quiet environments.

Acoustic issues for RC systems are different from those associated with conventional HVAC systems. In conventional HVAC systems the system is a noise generator and transmitter. In the case of RC systems, as the heat transfer surfaces are usually acoustically hard, this raises issues related to room acoustics; sound absorbing, sound transmitting, and sound reflecting. All these topics will be discussed in this research.

3.1.2.7 Visual performance

Visual comfort could be defined as the visual environment that supports the activities of the occupant (Reffat and Harkness 2001) and how easily one can view tasks. More often visual comfort is discussed in terms of discomfort glare, disability glare, and veiling reflections. High levels of any of these three conditions result in visual discomfort.

Four lighting factors affect visual performance and as shown in Figure 3.37:

a) Illuminance: lighting level and distribution.
b) Luminance ratios: brightness, contrast and glare.
c) Color rendition.
d) Occupancy factor and controls.

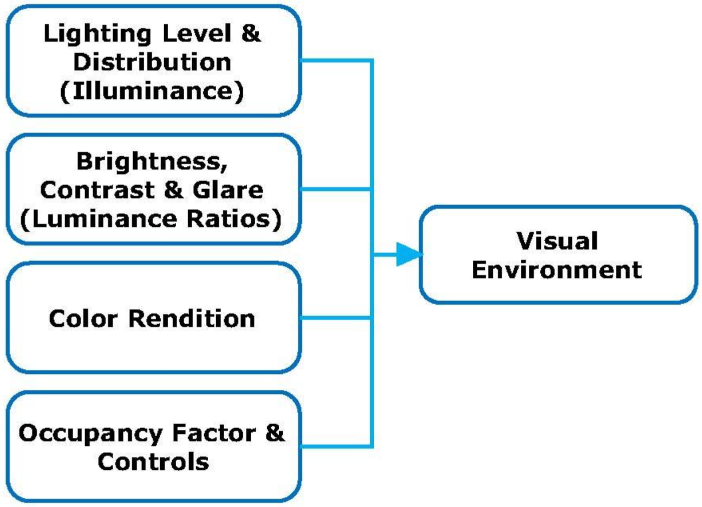


Figure 3.37. Variables affecting the visual environment

Rush (1986) identified the limitations of acceptable visual performance which may vary from one situation to another depending on a) age, health and eye health, b) type of function (Sense of calm or excitement, sense of spaciousness or intimacy, and sense of cheerfulness instead of gloom), c) the element of time and contact with nature, d) definition of personal territory, privacy, and sense of security on the one hand and lighting for visual communication and human contact on the other, e) aesthetic values, and f) economical limits.

While artificial lighting can provide acceptable levels of illumination to perform a given task, Boubekri, Hull, and Boyer (1991) stated that: "it is the qualitative, rather than the quantitative aspect of illumination that designers need to focus on". Research results showed that headaches and eyestrain were significantly reduced with the use of high frequency ballasts (Heerwagen 2000). One explanation for this, that artificial light does not have full color spectrum as daylight, this will put stress on the human brain trying to improve the clarity of the image.

A study by Heschong (1999) for Capistrano district's schools in California showed that 'green' schools with natural daylighting improve learning. "Students in classrooms with the most daylighting, progressed 20% faster in math and 26% faster in reading than students in classroom with the least daylighting". In research conducted by Heerwagen and Judith (2000) they reported "data from a field experiment by Wilkens et al (1989) shows that [the] incidence of headaches vary among workers as a function of the flicker frequency of the fluorescent lamps". The previous statements indicate that designers should focus on the lighting quality rather than its quantity.

Light could be introduced to the space using daylighting strategies or by using artificial lighting methods. However, RC systems can affect window size, ceiling height, and artificial light configurations, which in turn can influence light quality in the space under investigation. In the case of Radiant Cooling Ceiling Panel system (RCCP) there is potential integration with the artificial light systems. These situations will be explained in this research as part of the decision-making process.

3.1.2.8 Spatial performance

Spatial performance is concerned with "the design of individual spaces and their furnishings to provide the best support for individual activity; the aggregation of these spaces, to best support the needs of the activities as a whole; and the provision of conveniences or functional services such as circulation/transportation, electricity, security and telecommunication" (Rush 1986).

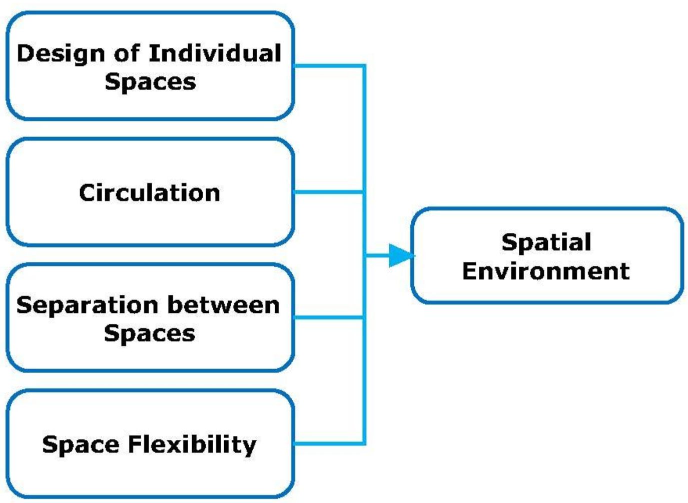


Figure 3.38. Some of the variables affecting the spatial environment

In this research, the relation between the use of RC systems and spatial performance issues such as circulation, separation between spaces, and space flexibility are discussed. Other issues related to spatial performance which may rise through the case studies and questionnaire will be identified.

3.1.3 Part Three: Energy consumption and cost

RC systems' energy consumption and cost are two important factors in determining the system applicability. The bigger scopes of this research are a) to assist architects and HVAC engineers to examine the applicability of implementing a RC system in a given space in the schematic design phase when details for system specification have not been established, b) understand the consequences of implementing a RC system in any given space in light of various building performance mandates, and c) this research has one cooling option, namely RC system, future research will include other cooling systems/strategies which makes the need for cost and energy comparison more reasonable for comparisons and making decisions. For this, the detailed discussion of these two factors as part of the decision-support framework will be left for future research. The following sections discuss main points related to RC system energy consumption and cost.

3.1.3.1 Energy consumption

There is a great movement among the discipline of the built environment to move towards high efficient buildings and improved indoor environmental quality. This movement is related to the concerns of the environmental impacts, sustainable resource consumptions, and human health and productivity. Options to replace energy-intensive systems such as conventional HAVC are discussed and investigated, other strategies such as optimized building envelopes and natural ventilation are also have the potentials to achieve the previous goals.

RC systems appear to have to potentials to address the energy efficiency concern while improving the indoor environment quality, if designed and implemented properly. The findings of many researchers suggest that the energy saving with the use of RC systems may be significant. However, these results depend also on the climate, building design, cooling system components and configurations, control and operation strategies, and integration with the ventilation system.

The energy saving when using RC systems is due to several reasons:

a) RC systems separate the cooling and ventilation tasks, the amount of air delivered is reduced to fulfill the ventilation requirements. This means a reduction in fan power which is one the largest energy consumption components in conventional HVAC systems.

b) Water can hold much more energy per unit volume when compared to air, which means moving energy around a building using a RC system is more energy-efficient when compared to using air. The energy consumed by the pumps to circulate the water is very low compared to the energy consumed by the fan to circulate the air.

c) RC systems operate with relatively high water temperature, around 60-65 °F, while conventional HVAC systems operate only with low water temperature, 40-45 °F, this means lower loads, size, and energy consumption of the chiller, or even opportunities to use low-energy sources of cooling water such as evaporative cooling or geothermal systems.

Moore (2008) compared the energy consumption of four different cooling methods in four different areas of the U.S using an energy simulation software during the cooling season, May to September. In his study, the system dynamic, thermal comfort, peak loads, and energy consumption of the cooling system was tested in a prototypical office building in Denver, Sacramento, Los Anglos, and San Francisco. The cooling strategies used in the study were as in the following:

a) The first strategy was a chilled slab systems with DOAS were both systems used indirect evaporative cooling resources. Both systems used closed-circuit cooling tower. The DOAS has a heat exchanger for sensible energy recovery and indirect-evaporative cooling of ventilation air.

b) The reference strategy and baseline strategy was a VAV system with an efficient water-cooled chiller and fully integrated control rests for supply air temperature and airside economizer operation.

c) The third strategy was a VAV system with the same configuration of the baseline system with waterside economizer or waterside free cooling (WSFC), which is the same cooling water source used for chilled slab scenario.

d) The fourth strategy was a VAV system with the same third method configuration and nighttime pre-cooling cycle.

The simulation results are shown in Figure 3.39, Figure 3.40, Figure 3.41, and Figure 3.42.

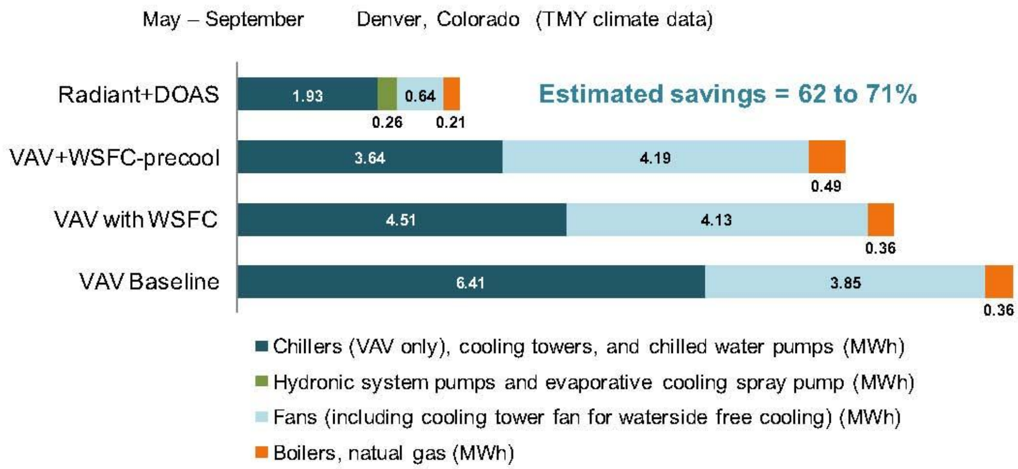


Figure 3.39. The simulation results of the energy consumption of the different cooling strategies for Denver, Colorado
Source: (Moore 2008)

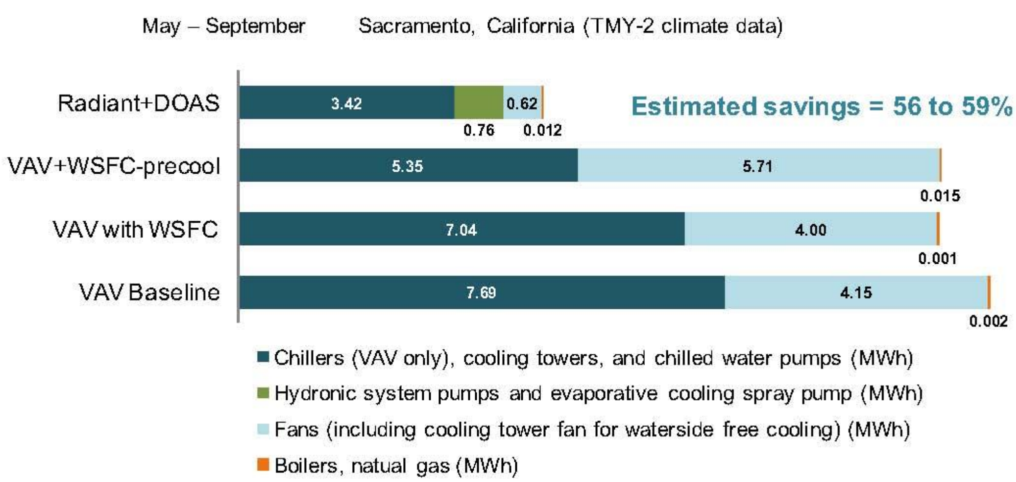


Figure 3.40. The simulation results of the energy consumption of the different cooling strategies for Sacramento, California
Source: (Moore 2008)

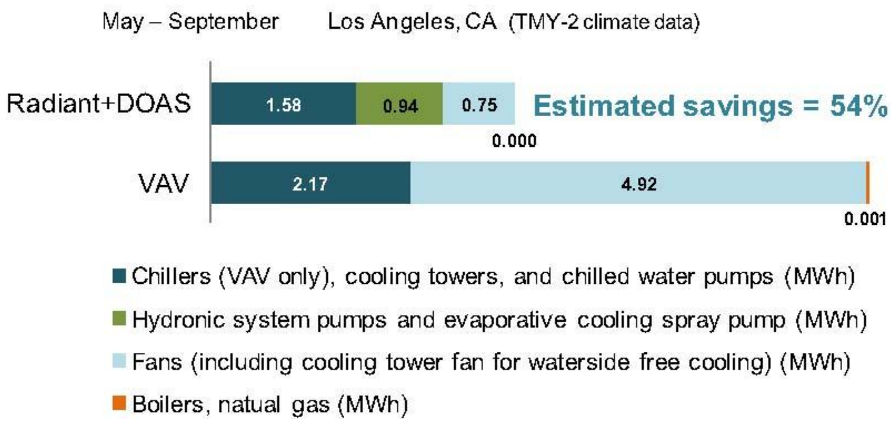


Figure 3.41. The simulation results of the energy consumption of two different cooling strategies for Los Angeles, California
Source: (Moore 2008)

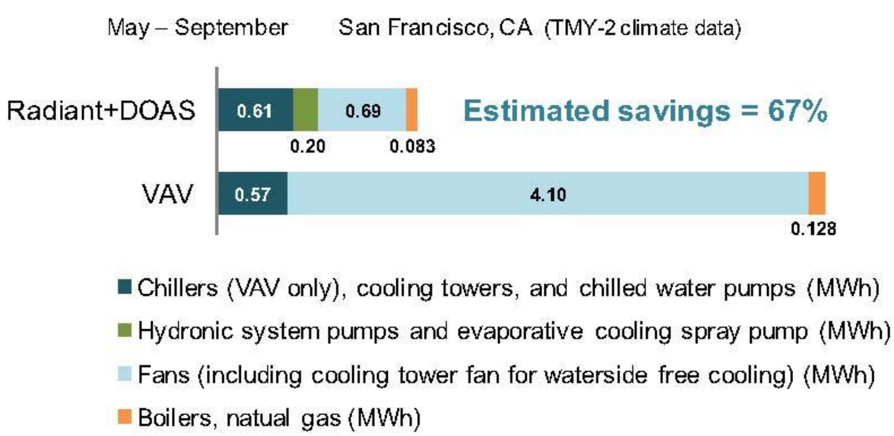


Figure 3.42. The simulation results of the energy consumption of two different cooling strategies for San Francisco, California
Source: (Moore 2008)

The previous results suggested a significant energy-saving potential for the RC system coupled with DOAS in all different climatic zones. The RC system and DOAS used an estimated 54% to 71% less energy than the standards VAV baseline even when VAV system was using waterside free cooling (WSFC) and nighttime precooling strategy. Moore (2008) explained the energy consumption reduction was mainly due to the use of the waterside free cooling and the reduced fan power.

Another important result the study revealed is the reduction in the peak power demand when using the chilled slab and the DOAS. The results in Figure 3.43 shows that the RC system and DOAS have about 34 hours of demand over the 5kW, while the VAV baseline has about 504 hours of operation over the same threshold during the cooling season, May to September.

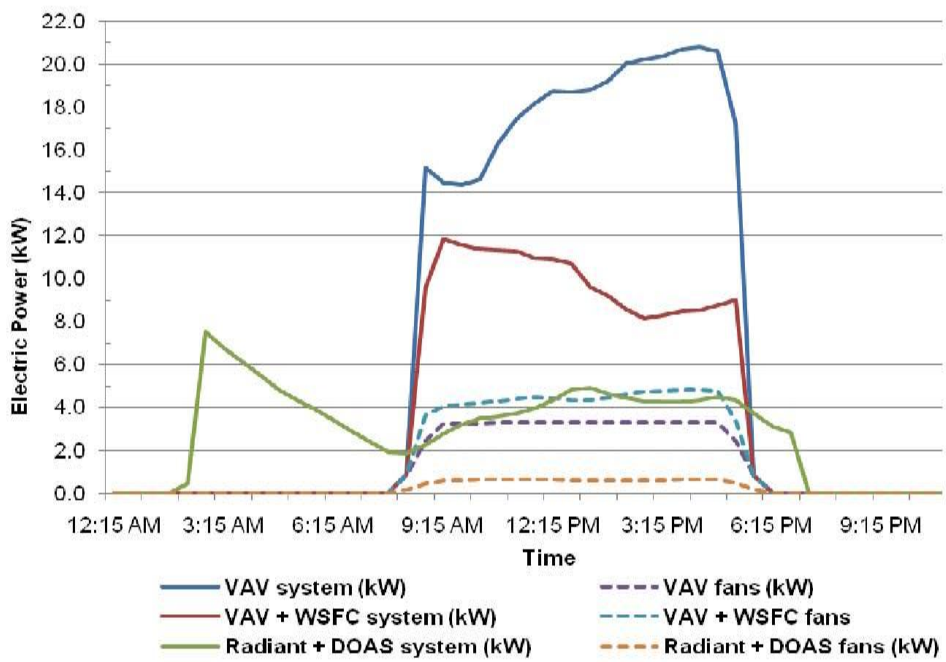


Figure 3.43. The peak power demand for the different cooling strategies for the day of peak cooling loads in Sacramento, California
Source: (Moore 2008)

In another study by Roth et al. (2002) they stated that the use of RCCP and DOAS could reduce the cooling and ventilation energy consumption by 25-30% when compared to a conventional VAV system. They explained this reduction of the energy consumption is due to the higher water temperature used in the RCCP systems, the reduction in the air volume need to be moved, and reduced ventilation flows to be cooled. They concluded that the use of RCCP, DOAS, enthalpy energy recovery, and system component diagnostics could save the U.S about 2.05 Quads annually in cooling energy compared to using conventional HVAC systems.

In conclusion, the use of RC systems in the built environment will significantly reduce its energy use. Energy use reduction is due to the following:

a) Water is a more efficient mean of transporting heat than water. The energy consumption of the water pumps to distribute water (heat) is significantly less than the energy consumption used by the fans in conventional HVAC systems (Tian and Love 2009; Medina and Young 2006; Miriel, Serres, and Trombe 2002).
b) RC system run with relatively higher water temperature when compared to conventional HVAC systems, this allow the utilization of low energy sources of water cooling (Moore, Bauman, and Huizenga 2006; Roth et al. 2002; Ardehali, Panah, and Smith 2004; Costelloe and Finn 2003).
c) The higher water temperature profile in RC systems means smaller chiller with improved performance; the peak demand is reduced and shifted to the off-peak operations (Hao et al. 2007; Simmonds, Mehlomakulu, and Ebert 2006; Olesen 2008).
d) With chilled slab system, it is possible to use low-energy nighttime strategy to precool the thermal mass and thus reducing the chiller loads during daytime (Moore 2008; Vangtook and Chirarattananon 2006).

3.1.3.2 Cost

RC systems are promoted as environmentally friendly systems and as systems which could improve the interior space performance at the micro-level. In practice, projects have limited budgets and the cost factor becomes a critical criterion for systems selection. Cost includes the initial, the operating, and maintenance cost of the system.

It is really hard to determine the exact capital cost of the RC implementation, as this depends on the market prices, contractors, and energy prices which may vary through locations and time. Also, when considering the RC systems cost, it is important to include the ventilation system cost. In general, Novoselac and Srebric (2002) explained based on a study by Handel et al. (1992) that the capital cost of combined systems (RCCP and displacement ventilation) is approximately 20% more expensive than VAV system for cooling loads of 20 Btu/hr•ft^2. However, the capital cost of the VAV increases significantly when the space cooling loads increase. Even this study was based in 1992 markets and calculations, current RC system experts validate the concept of this finding.

Roth et al. (2002) explained, in their study of 50 different opportunities for energy saving in commercial building HVAC systems, that in new construction, the installation costs of RC system with DOAS is similar to conventional VAV system in the U.S. market. They assessed that this is depend mainly on the RC system configuration and incorporation of other system components such as the need for separate system for heating. Their conclusion, of similar cost, depends on different sources and study finding done by different researches. On the other hand, Roth et al. (2002) explained when studying the payback time of 15 different HVAC options that RCCP and DAOS have an immediate payback time as shown in Figure 3.44.

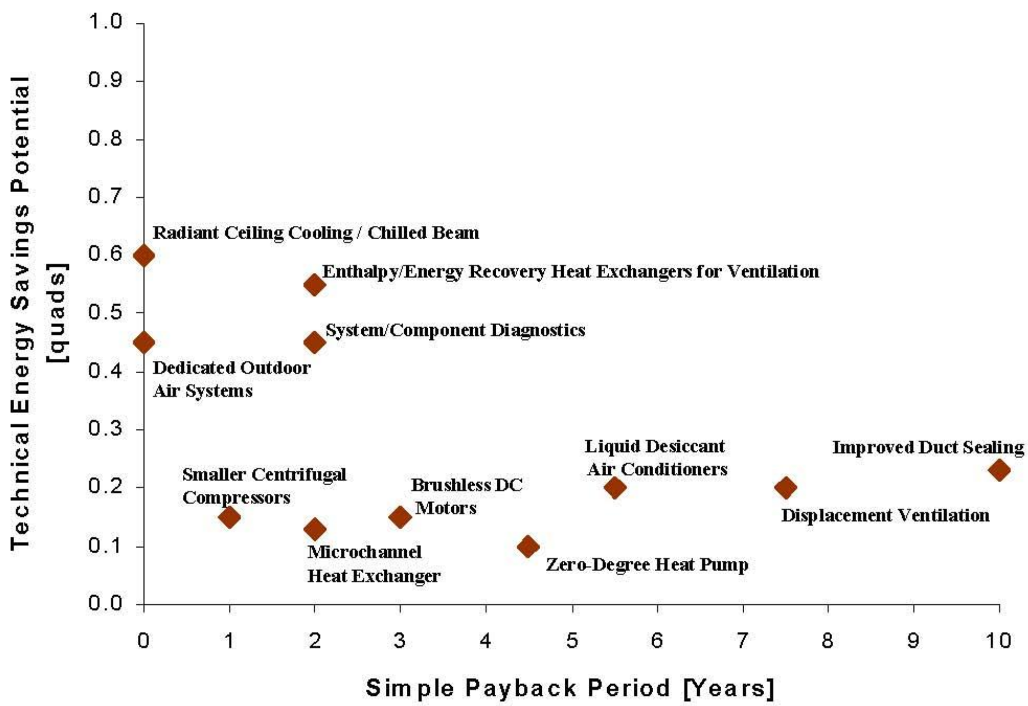


Figure 3.44 Estimated simple payback period for 15 different HAVC systems Source: (Roth et al. 2002)

When calculating the RC system cost it is important include they energy related benefits as explained in the discussion of the previous point, and other non-energy benefits such as down-sizing of the HVAC equipments, reduction of the energy peak demand, improved thermal and IAQ environments, and low maintenance cost.

In conclusion, the cost comparison between RC systems and other conventional HVAC systems is complex is variables depends on the market prices. Capital cost is an important factor for such comparison; however, the running cost which includes energy consumption and maintenance is another important factor to include. Other non-energy issues such as the thermal and IAQ environments are important to include when comparing HVAC systems. This complexity suggests developing a separate framework for cost comparison between different HVAC systems.

3.1.4 Part Four: Decision-support systems and the decision-making process

3.1.4.1 Introduction and definitions

A decision-support system is an analysis tool which provides structure and guidance for thinking systematically about certain decisions (Clemen 1996). On the other hand, a decision making system is a structured and systematic way that leads through the process of choosing among alternative courses of action for the purpose of attaining a goal or goals. In the architectural design process, which involves many trade-offs to reach the final optimal solution, decision-support systems seem to be more beneficial to designers and decision-makers than decision-making systems.

Another important feature of decision-support systems is that they do not claim to recommend an alternative, and instead of providing solutions, they provide insight about the situation, uncertainty, objectives, and trade-offs. They may yield or recommend a course of action, but that would not take over the decision-maker's job.

Decision-support systems are tools that could give decision-makers the needed knowledge and information, in a systematic and analytical way, to take action and make good decisions with confidence and clear vision about specific problems, where a good decision as defined by Clemen (1996) is the decision that gives the best outcomes.

(Clemen 1996) stated that, by better understanding the problem(s), through understanding the structure of the problem and the uncertainties in the trade-offs, the alternatives, and the outcomes, the decision maker may improve the chances of having better outcomes and most importantly minimize the chances of unlucky outcomes and unpleasant surprise.

Decision analysis tools as defined by Keeney and Raiffa (1993) are a "prescriptive approach designed for normally intelligent people who want to think hard and systematically about some important real problems". Having such perspective is important when making a consistent approach towards solving problems is a goal. Clemen (1996) stated that "experimental evidences from psychology shows that people generally do not process information and made decisions in ways that are consistent with the decision-analysis approach".

3.1.4.2 Purpose of the decision-support system

The decision-support system or analysis tools could help the decision maker in the following ways:

a) "Elements of a decision's structure include the possible courses of action, the possible outcomes that could results, the likelihood of these outcomes, and the eventual consequences to be derived from different outcomes" (Clemen 1996). Identifying these points through the framework would help to supplement one or more of the decision maker's abilities towards making good decisions (Holsapple and Whinston 1996). Also, the framework would help in the building performance evaluation during the pre-construction stage as explained in section 3.1.2.1, and thus maximize the space performance as desired.
b) Identify the sources of uncertainties in a systematic and useful way (Clemen 1996). This is an important step in the decision-making process.
c) Help to deal systematically with multiple objectives and trade-offs (Clemen 1996). This is an important feature, especially in the architectural discipline, as trade-offs are natural features of the architectural design process.
d) Decision-support systems aid decision makers in addressing unstructured or semi-structured decisions by managing and processing the available knowledge (Holsapple and Whinston 1996).
e) It could help to sort through and resolve differences of opinion between the decision-makers more smoothly and rapidly (Holsapple and Whinston 1996; Clemen 1996).

3.1.4.3 Decision making process

According to the Harvard Business School (2006), the process of making decisions, in general, consists of five steps. These steps follow the initial process of establishing a clear and meaningful object(s).

a) Establish a context for success. This step is related to the environment where the decision is discussed and made. This research acknowledged this point by identifying its main users: architects and HVAC system engineers.
b) Frame the problem properly. This frame is the mental window through which the decision-maker is looking to the problem. If the problem is framed correctly, the chance to make good decisions is increased. In this research, the problem is established as a decision-support framework by which the decision-maker will know whether the RC system is applicable for a certain space or not in any given project/building type, and what are the consequences of the RC implementation in terms of performance and other architectural decisions.
c) Generate and identify alternatives. Without alternatives, there is no decision to be made. Also good alternatives lead to good decisions. This research identifies the alternatives the decision-maker should consider in his/her decisions when implementing a RC system. Identifying these alternatives and choices will help with the design and application of RC systems.
d) Evaluate the alternatives. In this step, the decision-maker has to estimate how well each choice meets the objectives he/she established at the beginning of each project. This research assumes that the general objective is to optimize the performance of the interior environment according to a set of building mandates. This research identifies the evaluative criteria and leaves the evaluation process to its user.
e) The final step in the decision-making process is to choose the best alternative. In this research this implies selecting the alternative that makes the RC implementation successful through optimizing the performance of interior environment. Figure 3.45 summarizes the previous discussion:

The most critical point in making decisions is between identifying the alternatives and choosing the best alternative. Clemen (1996) refers to this stage as "modeling and solution". The focus in this stage is to decompose the problem to understand its structure and measure uncertainties and values.

The first level of the decomposing process is to structure the problem in smaller and manageable pieces, then model uncertainties and preferences. In this research, these models are established using influence diagrams and decision-tree techniques. These models will help in understanding the relationships between the framework inputs and the framework evaluative categories as identified in sections 4.2.1 and 4.2.3. Identifying the relationships through the modeling and solution stage could be considered as the central point of the proposed decision-support framework.

General Process of Making Decision	Research Interpretation
Establish a context for success	Framework users: Architects (mainly) and HVAC system engineers
Frame the problem properly	Is the RC system is applicable for the space under investigation? What are the consequences of the RC system implementation?
Generate and identify alternatives	Design alternatives and trade-offs when considering RC system implementation
Evaluate the alternatives	Identify the evaluative criteria: expected performance of the RC system according to the criteria of building mandates
choose the best alternative(s)	Left for the framework user

Figure 3.45. The general steps of the decision making process and their interpretation in this research

3.1.4.4 Sequential decisions and uncertain events

In general, there are two types of decisions: single decisions and sequential decisions, see Figure 3.46. Single decisions occur where there are at least two alternatives to choose from, and by choosing the best alternative the problem is solved. Sequential decisions occur where making one decision leads to another.

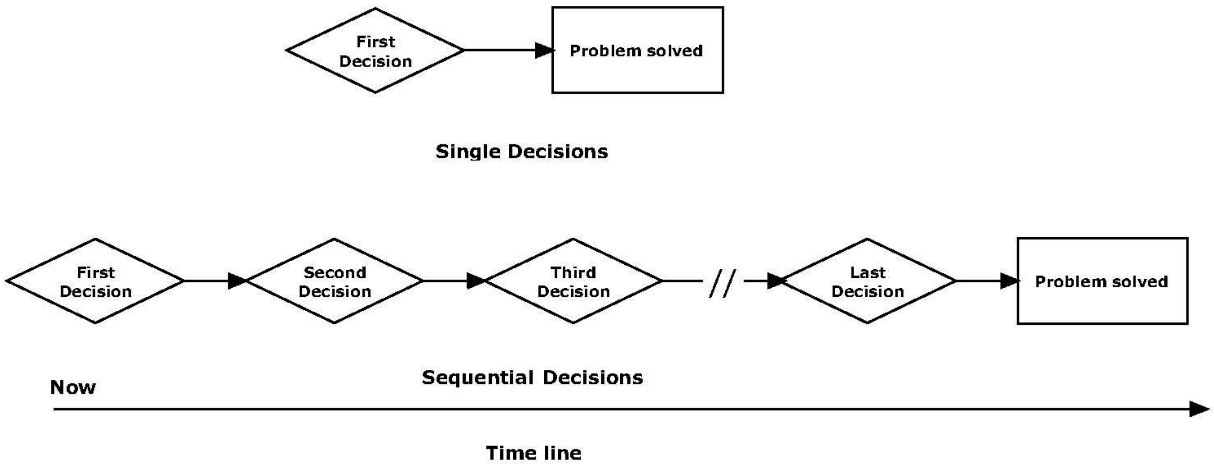


Figure 3.46. Decisions types
Source: Adapted from (Clemen 1996)

In sequential decisions situations, which are the normal scenario in the architectural discipline, the decision-maker needs to consider decisions to be made now and later, as future decisions often depend on previous decisions. Also, the decision-maker needs to identify the uncertainties of each decision (Clemen 1996). These two points are crucial to efforts of maximizing building performance through systems integration (Rush 1986).

Because decisions are about the future, each decision involves uncertainties. In sequential decisions, it is important to identify the areas of uncertainties, determine those which have greatest impact on the goals and objectives, and finally try to reduce the key uncertainties or even resolve them before making the next decision (Harvard Business School 2006). Including uncertain events in sequential decisions is shown in Figure 3.47. By making the last decision and resolving the final uncertain event, the decision-maker has completed the job, when the final consequence can be measured against the objectives. The time when the decision-maker achieves results is called the planning horizon (Clemen 1996).

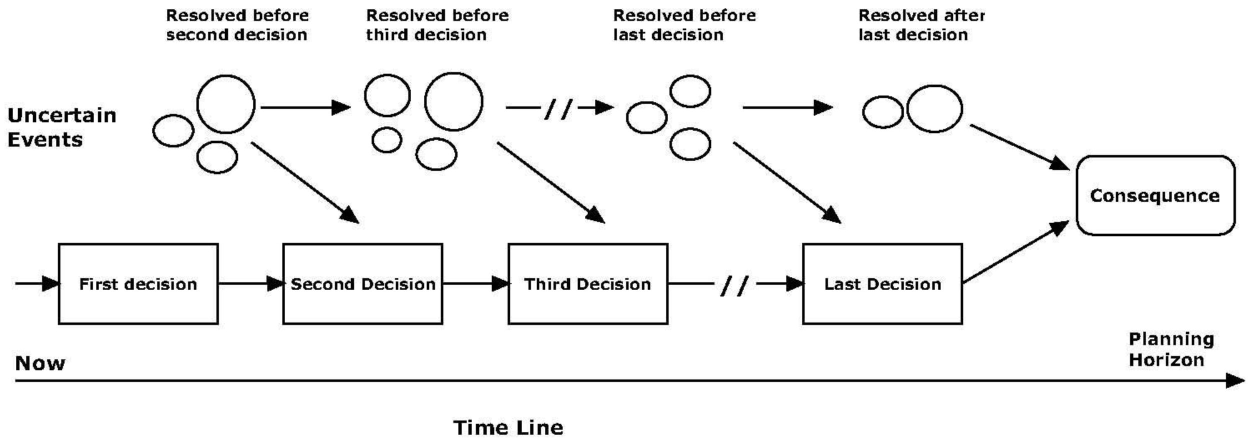


Figure 3.47. Uncertain events in sequential decisions
Source: (Clemen 1996)

3.1.4.5 Building the framework

By mapping and linking the decision-support framework inputs with the evaluative categories, the framework may be used to assist architects and HVAC engineers to examine the applicability of installing a RC system in a given space. Also this framework should help in understanding the consequences of implementing a RC system in any given space and for assessing the space for the evaluative categories as identified in section 4.2.3. The framework is not designed to make decisions; rather it is designed to help the user making the right decisions regarding RC system use and implementation.

Some of the framework inputs and evaluative categories are subjective and others are objective and that makes their relationships complex in some cases. For these reasons, the decision-support framework must be grounded in a comprehensive decision-making theory. The foundation which was applied in this research is the Choosing By Advantages (CBA) decision making system. Suhr (1999) explained that “CBA is not an individual method for making decisions, it is not a tool, and it is not a collection of methods. It is a decision-making system”.

It is important to notice that the CBA is designed to make decisions, while the purpose of this framework is help in the decision-making process. This suggests the need to design the framework in a way to be easily integrated with the CBA decision making system.

For the CBA, a decision cannot be made without having different alternatives or options. For this research the alternatives are whether to select a RC system or not and what type of RC system to implement. In CBA the general path to making a decision according to the tabular method is as in the following:

a) “Summarize the attributes of each alternative”.
b) “Decide the advantages of each alternative”.
c) “Decide the importance of each advantage”.
d) “Choose the alternative with the greatest total importance of advantages”, if all alternatives have the same money value.

To adapt the CBA system to this research, this research summarizes the attributes of using a RC system in a building by mapping the different variables and connecting the inputs with the evaluative categories as explained in section 4.6. Future research may study other cooling strategies or system options.

Although beyond the scope of this research, when the decision-maker has analyzed many options he/she can compare two or more alternatives to see the advantages of each then decide the importance of each advantage to choose the best cooling system for the situation under investigation. Figure 3.48 shows the relationship of this research, to future work and the CBA decision making system.

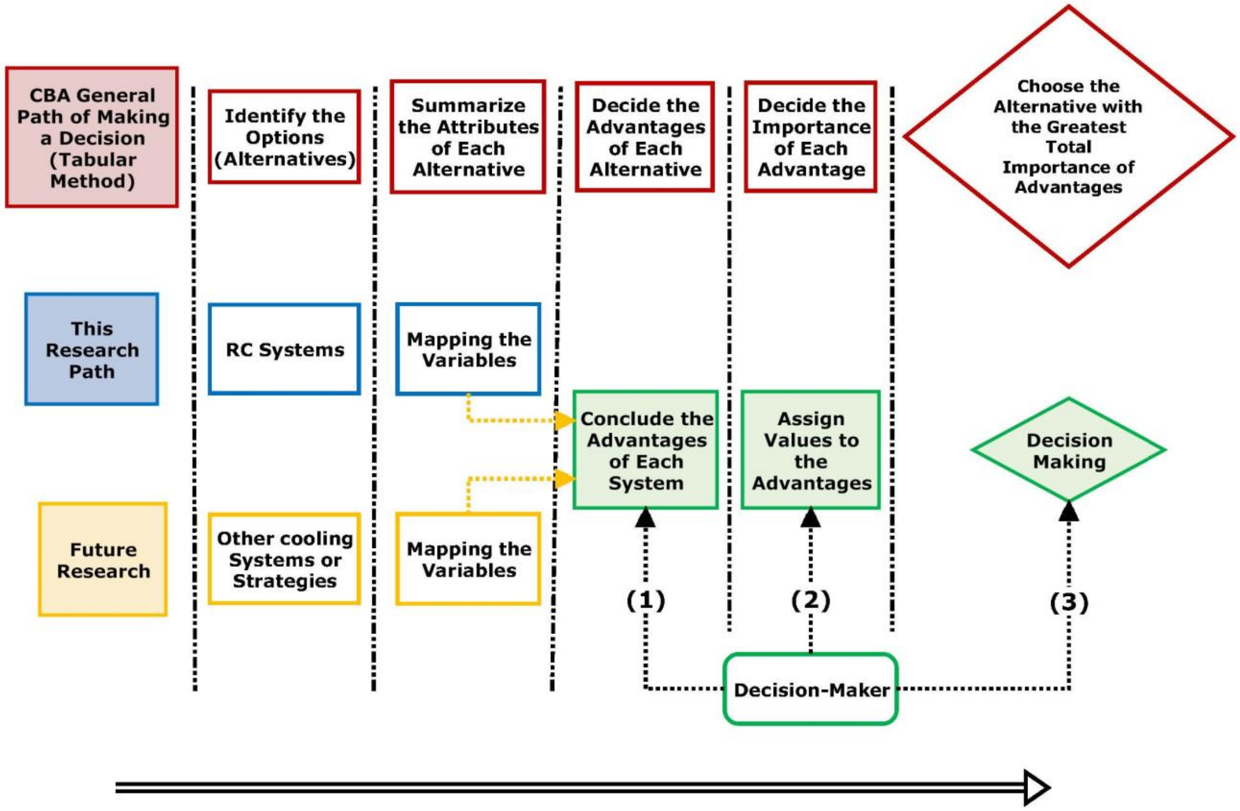


Figure 3.48. Relationship between this research, future work, and the CBA decision making system

The first row of Figure 3.48 shows the general path to make a decision according to the tabular method in the CBA. This research, as shown in the second row, performed the first two steps as there is only one cooling option, namely RC systems. Future researches which may discuss and analyze other cooling systems, will allow the decision-maker(s) to choose from different cooling systems the most suitable for the space/building under investigation using the tabular method as described in the CBA decision making system.

3.1.4.6 Conclusion

In the architectural design process, which involves many trade-offs to reach the final optimal solution, designers and decision-makers need an analysis tool with which to structure the problem and give guidance for thinking in a systematic way. This decision analysis tool is called a decision-support system. A decision analysis tool gives the needed knowledge and information to better understand the problem to take actions and make good decisions.

There are two types of decision; single decisions and sequential decisions. In sequential decisions the decision-makers need to consider future decisions as they often depend on previous decisions. In sequential decisions, uncertainties to be identified and understood are to be reduced to the minimum as they may impact the pre-determined goals and objectives.

The decision-support framework developed in this research may be used to assist architects and HVAC engineers to examine the applicability of installing a RC system at any given space. Also, this framework should help in understanding the consequences of implementing a RC system in any given space.

The framework is grounded in a comprehensive decision-making theory; Choosing By Advantages (CBA). This makes the framework open for future development where RC systems are alternatives among other cooling systems as shown in Figure 3.48.

3.2 Sources of Relevant Knowledge: Case Studies

3.2.1 Introduction

The case studies are the second source of the relevant knowledge in this research as discussed previously in the research methodology. The information extracted from these case studies will influence the development of the framework by providing practical information for the design and implementation of RC systems. The case studies were analyzed according to a set of topics revealed from the initial framework that emerged from the systematic literature review. After analyzing each case study individually, their findings were grouped and used to develop the final proposed framework which is presented in chapter four.

3.2.2 Case one: Housing for Kripalu Center for Yoga and Health, Stockbridge, Massachusetts

3.2.2.1 Building description

The building which is located in Stockbridge, Massachusetts has eighty guest rooms with private baths, a multi-purpose hall, and a Yoga studio on the ground floor. The building is five-stories with a total area of 33,000 ft^2. The building was completed in 2009 and received the AIA (American Institute of Architects) National housing Award in the category of Specialized Housing in 2010 (Moe 2010).

3.2.2.2 Radiant system

The building is heated and cooled using radiant systems where tubes carrying the hot and chilled water are embedded in the lower portion of the concrete slabs so radiant heat exchange will be asymmetrical toward the ceiling sides. The floor sides and the ceiling sides of the chilled slab are uncovered so the radiant cooling and heating will occur in both directions. The ceiling thickness is 7.75 inches (Moe 2010).

3.2.2.3 System cooling capacity

No available information.

3.2.2.4 System surface temperature

No available information.

3.2.2.5 System control

The building is zoned into east and west zones to respond to variable solar gains. Corridors are not conditioned. Guest rooms and the multipurpose hall are conditioned. All guest rooms have in-wall fin tube hydronic convertor units to cool the fresh outdoor air and to allow individuals to set the temperature inside their rooms to the desired setting (Moe 2010; Giovannini 2011).

3.2.2.6 System physical properties

The radiant system uses the building structure, namely the slabs, as the heating and cooling surface. As explained by the architect Peter Guggenheimer, inside the guest rooms, the ceiling and floor sides of the chilled slab are not covered or even painted for better thermal heat exchange and for aesthetic purposes (Moe 2010).

3.2.2.7 Designers' and clients' goals and preference

According to the architect, the radiant system was implemented to reduce energy consumption while providing a high quality environment (Cilento 2010).

3.2.2.8 Codes and Standards

The building was designed and constructed according to the American codes and standards.

3.2.2.9 Climate (Outdoor environment)

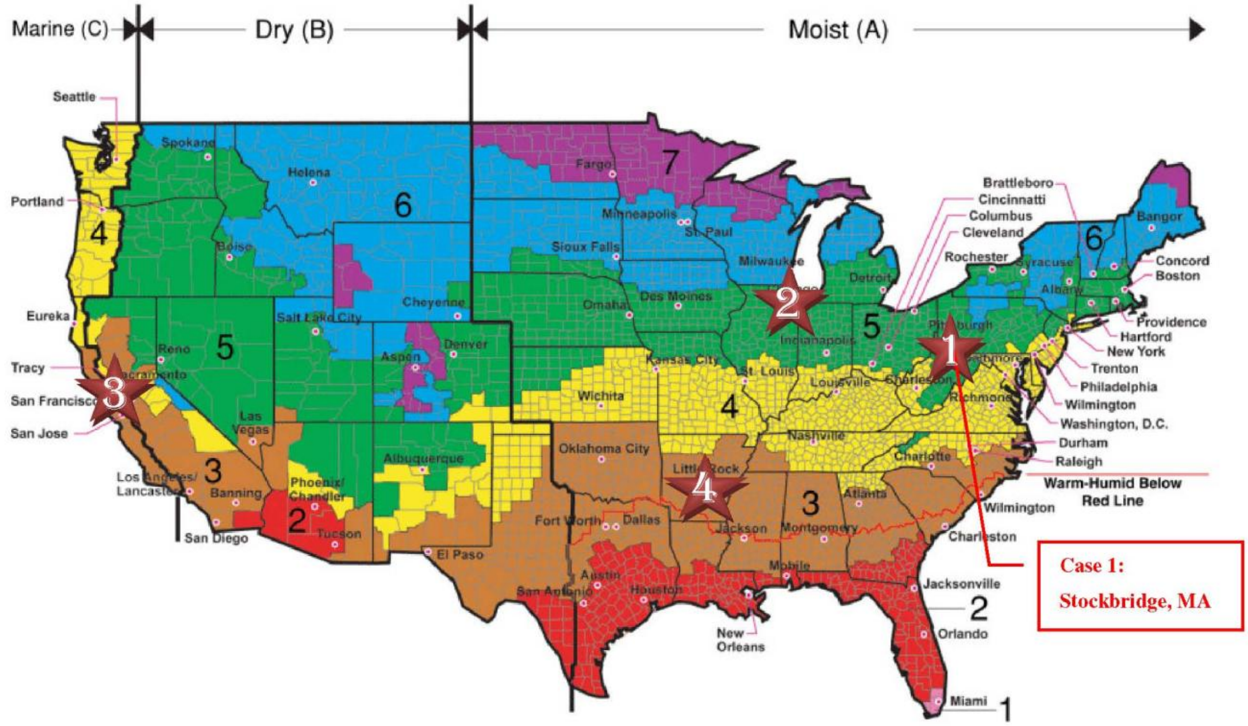


Figure 3.49. The location of case no. 1 in the climate zone map of the United States
Source: (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010)

According to Figure 3.49 Stockbridge is located in a cool-dry climate zone, which is defined as “a region with between 5,400 and 9,000 heating degree days (65 °F base)” (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010). According to the Köppen climate classification Stockbridge has a humid continental climate, with warm and humid summers and cold and snowy winters. Table 3.4 summarizes the average weather data for Stockbridge, MA.

Table 3.4. Climate data (Average weather) for Stockbridge, MA [1]
Source: (World Climate 2007; Software 2011)

Statistic	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Minimum Temperature	°F	12.7	14.3	23.3	33.5	43.4	51.8	56.9	55.6	47.6	36.9	29.5	18.9	35.37
Maximum Temperature	°F	32.5	35.8	45.1	57.6	69.6	77.4	81.3	79.3	71.2	60.1	48.4	36.6	57.91
Heating Degree Days (65 °F base)		1287	1166	976	577	341	121	60	86	212	520	768	1173	Total 7287
Cooling Degree Days (65 °F base)		0	0	0	18	48	103	180	147	61	11	0	0	Total 568

3.2.2.10 Space function

Guest rooms were designed for one or two guests. The multipurpose hall is mainly used to practice Yoga. Internal heat gain was kept to a minimum by having low occupant density and a minimum amount of electrical equipment in the guest rooms (Moe 2010).

3.2.2.11 Space characteristics

The guest rooms were designed to be economical in plan and section. Room dimensions are 9 feet and 9 inches by 19 feet with a floor to ceiling height of 8 feet. Each room has an operable window with exterior sun shading. Ceiling and floors are uncovered with minimal covering for the walls (Giovannini 2011).

3.2.2.12 Construction system

The building slabs and columns are concrete. Since all systems are vertically distributed, this allows the architect to maximize the volume and number of the guest rooms. The total height of the building is 50 feet and the net to gross ratio (areas that are assigned to a function / total area to the outside walls) is about 1.29. Through the compact building design, the guest rooms are 30% smaller in volume when compared to typical construction (Moe 2010; Dassler 2010).

[1] HDD and CDD were generated using Degree Days.net software. The numbers shown in the table are the average for the years 2006-2010 for the weather station located in Pittsfield Municipal Airport, MA.

3.2.2.13 Envelope configuration

The building structure is all concrete. As expressed by the designer, most of the inside surfaces are left exposed for better thermal heat exchange and for aesthetic purposes. The building is highly insulated, and 30% of the envelope is glazed openings. The operable windows in the guest rooms are sun-shaded to minimize solar heat gain. The multipurpose hall on the ground floor has large glazed windows (Cilento 2010).

3.2.2.14 Heating, cooling, and ventilation

The building is shaped to capture and channel wind. All guest rooms have operable sliding windows which can be controlled manually by occupants to allow fresh air into each room. Corridors could be naturally ventilated. The duct system in the building supplies fresh air to the rooms. The multipurpose hall in the ground floor is equipped with additional ventilations system and humidity control (Moe 2010; Dassler 2010).

Corridors are not conditioned, except small electrical heaters are used near glazed spaces at the end of each corridor. Small air units in each room are used for air exchange and humidity control (Moe 2010).

3.2.2.15 Energy use

Energy analysis shows that the thermally active slab in the building would use almost two-thirds of the annual energy when compared to a conventional all-air system (Moe 2010; Dassler 2010).

3.2.2.16 Lighting

Windows allow daylight penetration to minimize the use of electrical lights during the day (Moe 2010).

3.2.2.17 Additional points

Staff and guests are informed about the basics of the systems and how to properly operate them. There is a text posted in each room that explains the efficiencies and function of the building, and suggests where to position the screen when away to minimize the energy consumption.

The slab system was activated during the construction period with domestic hot water heaters during cold winters to provide a thermally comfortable environment for the workers (Giovannini 2011; Moe 2010).

All mechanical systems were vertically distributed in chases between units to keep the floors and ceilings free from any interruptions (Moe 2010).

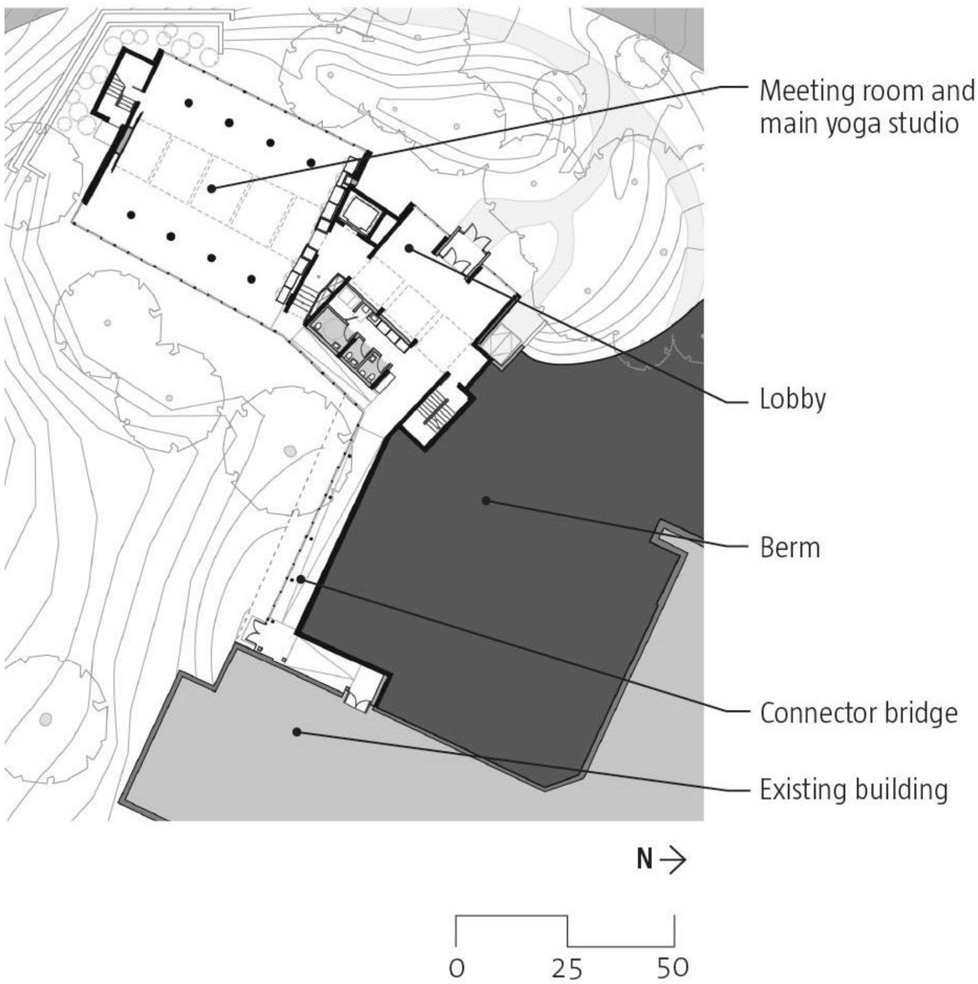


Figure 3.50. Ground floor plan
Source: (Peter Rose and Partners 2009)

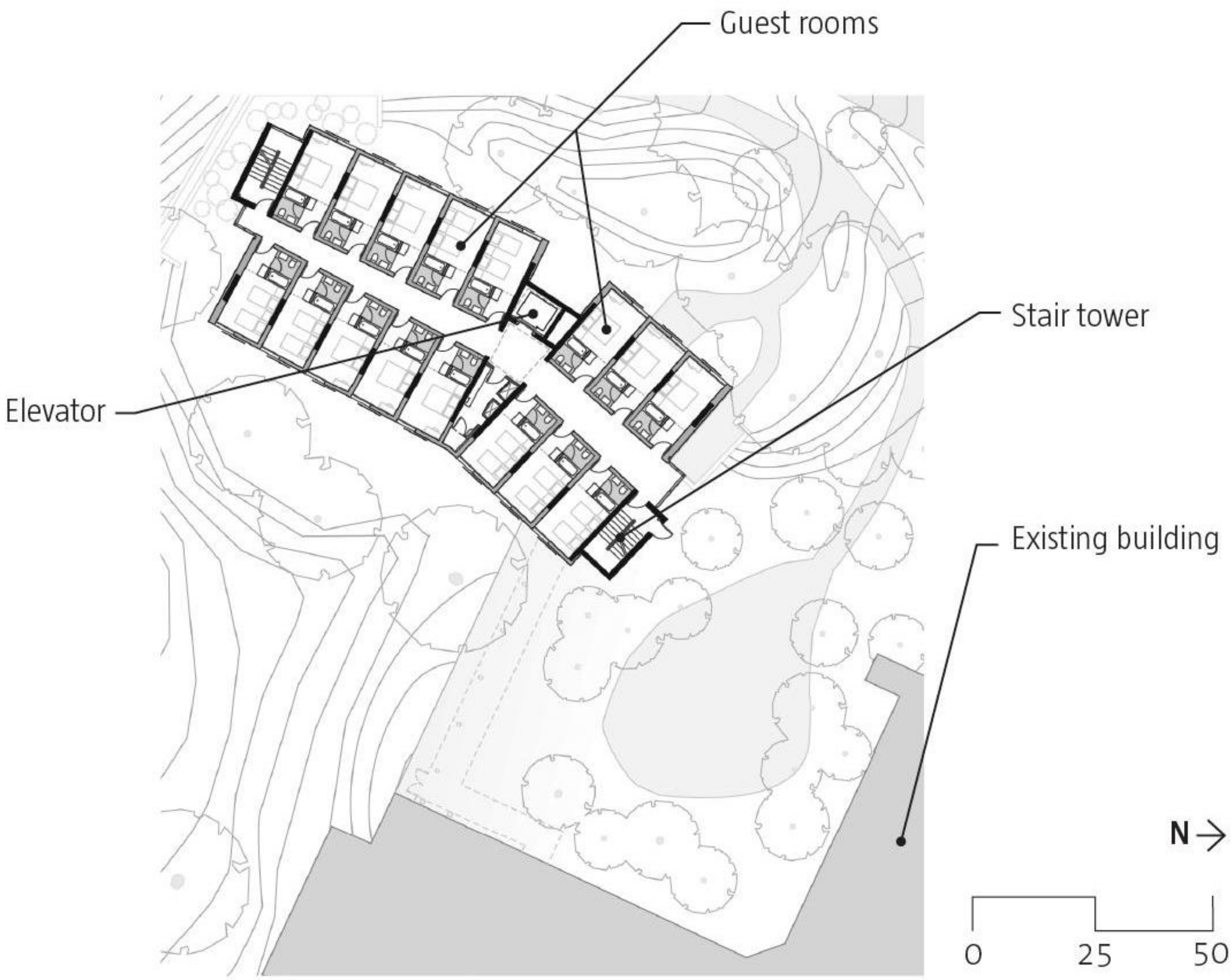


Figure 3.51. Floor plan of the guest rooms
Source: (Peter Rose and Partners 2009)

Figure 3.52. Front view of the Kripalu Center showing the shaded main (east-north) façade
Source: (Peter Rose and Partners 2009)

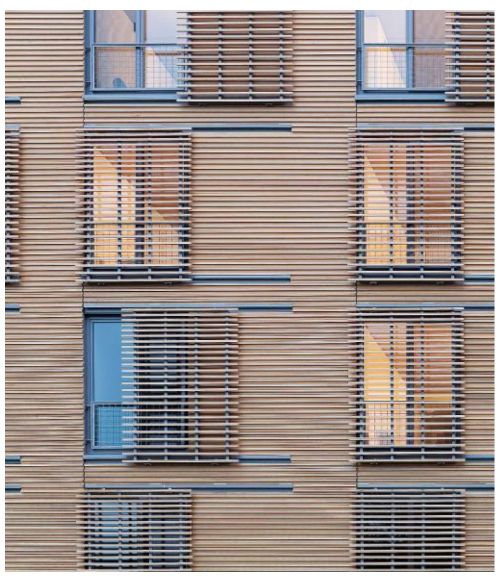


Figure 3.53. Window shadings can be operated manually as occupants desire
Source: (Peter Rose and Partners 2009)

Figure 3.54. A typical unit interior; showing the exposed ceiling for heat exchange
Source: (Peter Rose and Partners 2009)

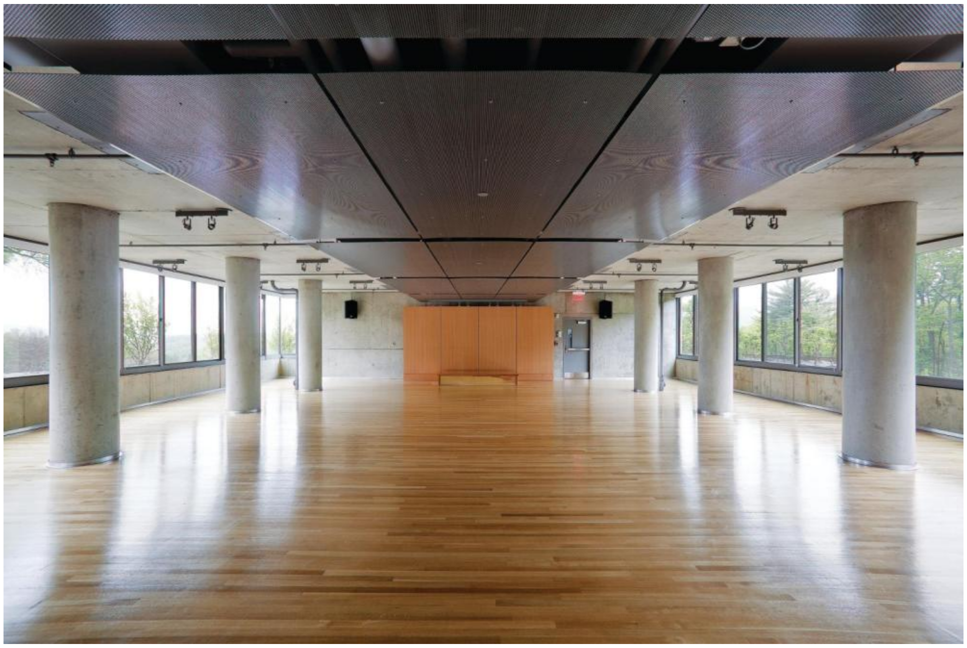


Figure 3.55. The multipurpose hall interior; ceiling partially exposed and large windows
Source: (Peter Rose and Partners 2009)

3.2.3 Case Two: Klarchek Information Commons, Loyola University, Chicago, Illinois

3.2.3.1 Building description

This project is a three-story LEED silver certified building, which was completed in 2007. The building is a 70,000 ft^2 digital research library for students and faculty of the Loyola University located on the edge of Lake Michigan. The building has 220 computer work stations, 35 group study rooms, and 8 classrooms. The main axis of the building runs directly north-south, which leaves the large glass walls facing west and east towards Lake Michigan (Moe 2010).

3.2.3.2 Radiant system

The slab is a thermally active surface for heating and cooling. The hydronic tubes were embedded in pre-cast vaulted planks to increase the effective surface area of the radiant heat transfer of the ceiling side. On the floor sides, there is a raised floor for cable management and displacement ventilation system for ventilation and humidity control. The spiral pattern of the tubing was incorporated to minimize temperature gradients across the slab. Tubes diameter is 5/8 inches with 6 inches spacing (Lavan and McLauchlan 2008).

3.2.3.3 System cooling capacity

The radiant cooling system was designed to meet 60% of the sensible cooling loads with cooling capacity around 13 Btu/h• ft^2 (42W/m^2) (Lavan and McLauchlan 2008).

3.2.3.4 System surface temperature

No available information.

3.2.3.5 System control

The Building Automation System (BAS) controls the operations of the vents, windows opening, blinds, and all ventilation and cooling modes. These operations are based on monitoring of the indoor and outdoor climates by the BAS. The BAS maintains the slab surface temperature in the cooling mode between 62 °F and 67 °F as required for cooling, or 3° higher than the indoor dew point temperature. Occupants do not have any control of the indoor environment.

The system is divided into three zones; the east, the west, and center zone (Lavan and McLauchlan 2008; Moe 2010).

3.2.3.6 System physical properties

The active slab system covers 80% of the total ceiling area. The vaults are painted white to help diffuse the light from the fluorescent lights centers in each vault. The vaults finishing material is concrete (Lavan and McLauchlan 2008).

3.2.3.7 Designers' and clients' goals and preference

The building was constructed in a popular open space viewing the Lake. The client and the architect, Devon Patterson, wanted a transparent building to keep the lake view, while also creating energy efficient building. The thermally active slab system helped in keeping the slab depth to the minimum to capture and channel the views. This also contributed in the total energy saving strategy (McLauchlan and Lavan 2010).

3.2.3.8 Codes and Standards

The building was constructed according to the American building codes and standards.

3.2.3.9 Climate (Outdoor environment)

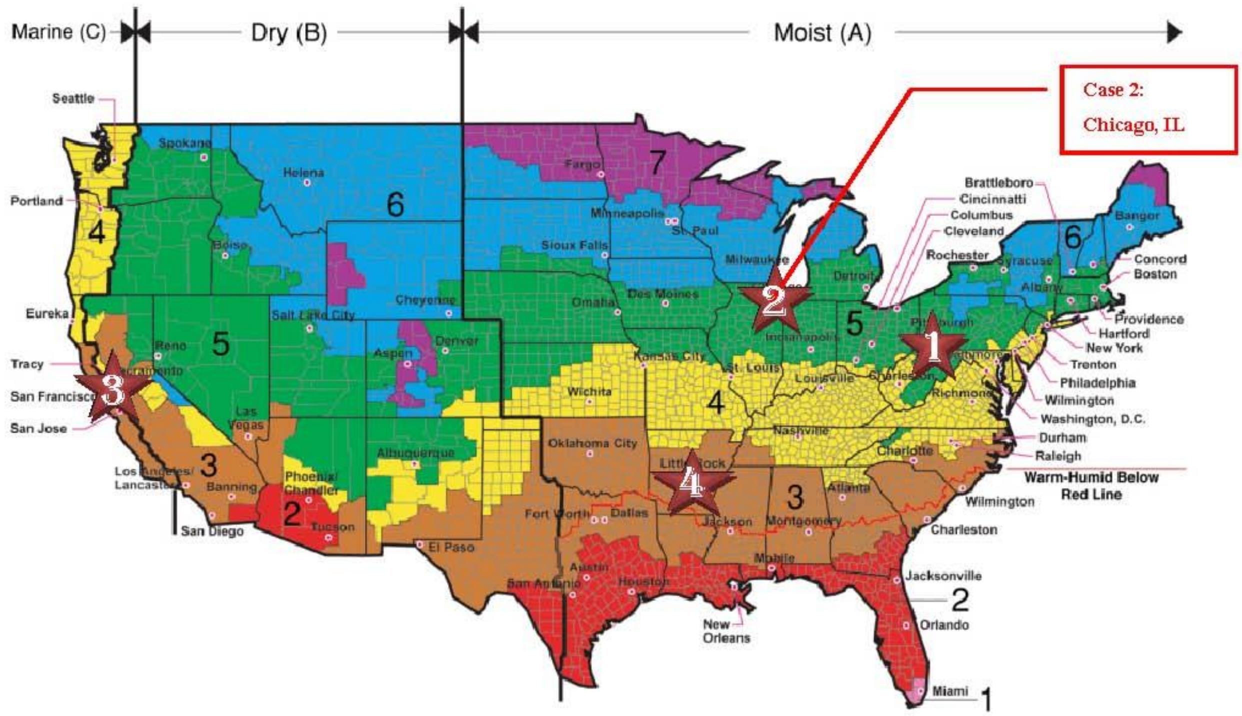


Figure 3.56. The location of case no. 2 in the climate zone map of the United States
Source: (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010)

According to Figure 3.56 Chicago is located in a cool-dry climate zone, which is defined as "a region with between 5,400 and 9,000 heating degree days (65 °F base)" (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010). According to the Köppen climate classification Chicago has a humid continental climate, with four seasons: cold, windy, snowy winters; mild springs; hot and humid summers; and crisp and relatively short autumns. Table 3.5 summarizes the average weather data for Chicago, IL.

Table 3.5. Climate data (Average weather) for Chicago, IL [1]
Source: (World Climate 2007; Software 2011)

Statistic	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Minimum Temperature	°F	18.3	23.9	32.2	41.5	51.3	60.8	66.3	65.3	57.4	46.2	35.1	23.5	43.48
Maximum Temperature	°F	32.2	37.4	47.4	58.9	70.2	80.3	84.4	82.7	76.2	64.3	49.4	37.1	60.04
Heating Degree Days (65 °F base)		1232	1127	792	464	234	57	20	19	107	396	697	1181	Total 6326
Cooling Degree Days (65 °F base)		0	0	4	28	85	208	311	297	119	33	2	0	Total 1087

3.2.3.10 Space function

The building has 220 computer work stations, 35 group study rooms, and 8 classrooms. The most common activity is office activities with met activities of 1.0 met to 1.2 met (Lavan and McLauchlan 2008).

3.2.3.11 Space characteristics

The west and east sides of the building (the longest sides) are fully glazed. The eastern side has a single layer insulated glazed envelope. The western side is a double façade system. The floors are raised, and the ceilings are painted concrete. The building has an open floor plan (Moe 2010).

3.2.3.12 Construction system

The building structure is mainly pre-cast concrete, with concrete columns (Moe 2010).

3.2.3.13 Envelope configuration

The envelope was designed to capture and to respond to views, solar radiation, daylight, and air flow. The east façade is a single layer glazed envelope of insulated low-E, low-iron, and argon filled units, with some automated operable panels at the ceiling heights. The west façade is a double envelope system where both layers are made of insulated glazing units. The cavity of

[1] HDD and CDD were generated using Degree Days.net software. The numbers shown in the table are the average for the years 2006-2010 for the weather station located in Chicago O'Hare international Airport, IL.

the western façade has horizontal blinds for solar gain and glare control. The west façade provides a thermal buffer and also plays an important role in ventilation and heat removal. When the blinds are closed in the west façade, they block about 92% of the luminous energy while still allowing views to the lake (Moe 2010; Lavan and McLauchlan 2008; McLauchlan and Lavan 2010).

3.2.3.14 Heating, cooling, and ventilation

There are four operating modes for maintaining indoor comfort:

a) Heating mode: when outside temperature is below 55 F. The space air temperature is maintained at 71 °F (+1.5 °F). The slabs emit radiant energy, all operable windows are closed, displacement ventilation is used for ventilation, and perimeter heaters are used on the eastern façade.
b) Cooling mode: when outside temperature is 75 °F and above. Windows in the east façade are closed, dampers at the top of the west façade cavity are open to exhaust hot air. The slabs absorb heat from the space (Radiant cooling). The BAS monitors and controls humidity levels.
c) Full outside air mode: when the outside temperature is between 55 F and 68 F the building operates in a natural ventilation mode. Windows of the west and east façade open automatically. The mechanical ventilation is shut down. If RH or moisture rises above certain values where condensation may occur on the ceiling, the BAS will close the windows and run the mechanical ventilation system.
d) Hybrid cooling mode: when the outside temperature is between 68 °F and 75 °F, the building vents are open and slabs are removing heat from the building through radiant cooling. The ceiling temperature is kept 5 °F above the indoor dew-point in this mode (Lavan and McLauchlan 2008; Moe 2010).

Mechanical ventilation systems

In the main floors of the library, the displacement ventilation system provides fresh air and controls humidity in all operating modes. The classrooms and seminar rooms at the bookends of the building have a separate VAV ceiling system to respond to the variable cooling loads that may happen there. These systems are designed to provide cool and dry air, as this will help in dehumidifying the main space since there is no vapor barrier between the spaces.

The amount of outside air required for ventilation and to maintain IAQ is controlled by CO_2 sensors installed throughout the space (Lavan and McLauchlan 2008).

3.2.3.15 Energy use

The building energy consumption is about 50% less than ASHRAE 90.1 base building (Moe 2010).

3.2.3.16 Lighting

The BAS controls the light automatically. Occupancy sensors are used in all rooms (McLauchlan and Lavan 2010).

3.2.3.17 Additional points

In the cooling mode, the return water to the central plant is used to chill the ceilings. This would increase the return water temperature to the central chiller and thus increase the overall efficiency of the chiller. The same technique is used in the heating mode (McLauchlan and Lavan 2010; Lavan and McLauchlan 2008).

Figure 3.57. West façade of the Klarchek Information Commons building
Source: (Moe 2010)

Figure 3.58. Section-perspective diagram showing different strategies, including radiant cooling system, used in the building to maximize the performance and minimize energy consumption Source: (Moe 2010)

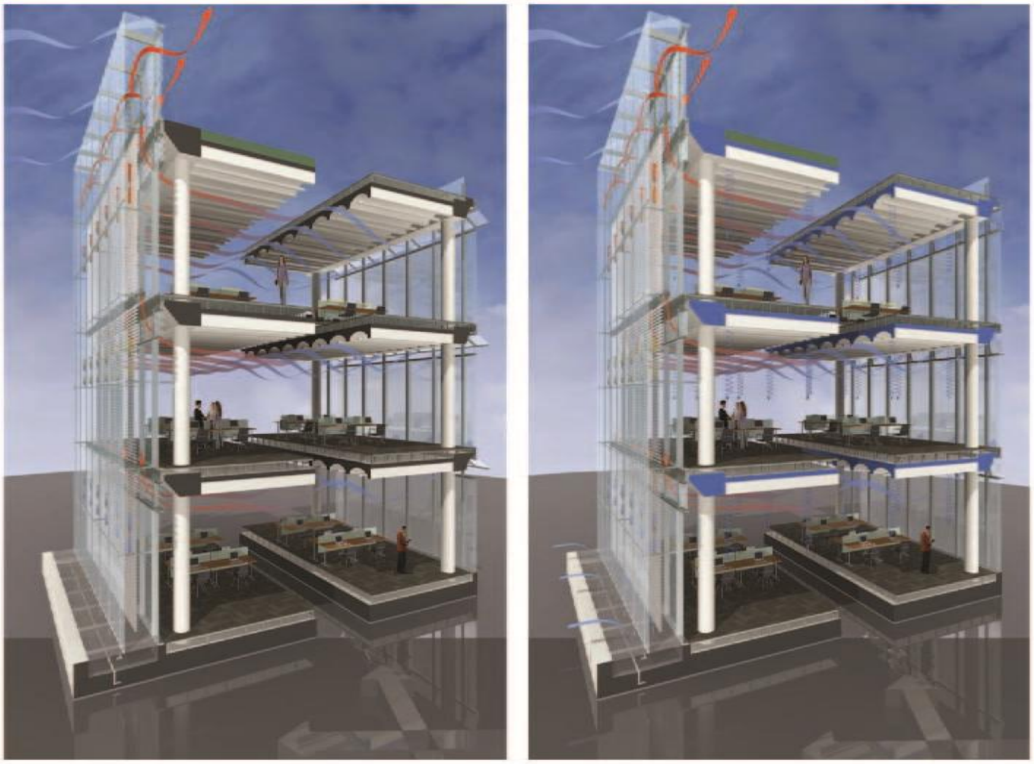


Figure 3.59. (Left) Natural ventilation mode (Right) cooling mode with radiant cooling system
Source: (Moe 2010)

Figure 3.60. View to lake of Michigan, vaulted radiant ceiling
Source: (Moe 2010)

3.2.4 Case Three: David Brower Center, Berkeley, California

3.2.4.1 Building description

The four-story building has a total area of 45,000 ft². The building includes office spaces, meeting rooms, theater, and restaurant. The building was completed in 2009 and has a LEED Platinum certification. The building also won first place for the 2011 ASHRAE Technology Award (Rumsey and Weale 2011).

3.2.4.2 Radiant system

The building uses a radiant slab system for cooling and heating purposes in three of its four floors, where ceilings are the active sides. The 5/8 inch diameter tubes lay in the concrete slab with 12 inches spacing between the centers (Miazga 2011).

3.2.4.3 System cooling capacity

No available information.

3.2.4.4 System surface temperature

The slabs have a set-point temperature of 70 °F (Miazga 2011).

3.2.4.5 System control

Although the building is connected to a Building Management System (BMS), it allows the users to analyze outputs and make informed decisions to adjust operation and energy use. The BMS also quickly diagnoses equipment status, alarms, and maintenance items. The BMS controls the radiant slab surface temperatures, indoor RH, and the interior temperature set-points.

Each floor is divided into five zones, where each zone can be heated or cooled separately (Miazga 2011; Rumsey and Weale 2011).

3.2.4.6 System physical properties

The system covers the entire ceiling of the three upper floors with a total area of approximately 31,500 ft². All floors are raised except the ground floor, this makes only the ceiling surfaces of the slab active. The ceiling surfaces are typically left exposed for better heat exchange with a few areas painted (Rumsey and Weale 2011).

3.2.4.7 Designers' and clients' goals and preference

According to the architect, Daniel Solomon, the goal was to design a building using the latest in energy-saving technologies and recycled building materials to minimize the carbon footprint while taking into account the life-cycle cost of the building construction, operation, and maintenance (Rumsey and Weale 2011).

3.2.4.8 Codes and Standards

The building was built and designed according to the American building codes and standards.

3.2.4.9 Climate (Outdoor environment)

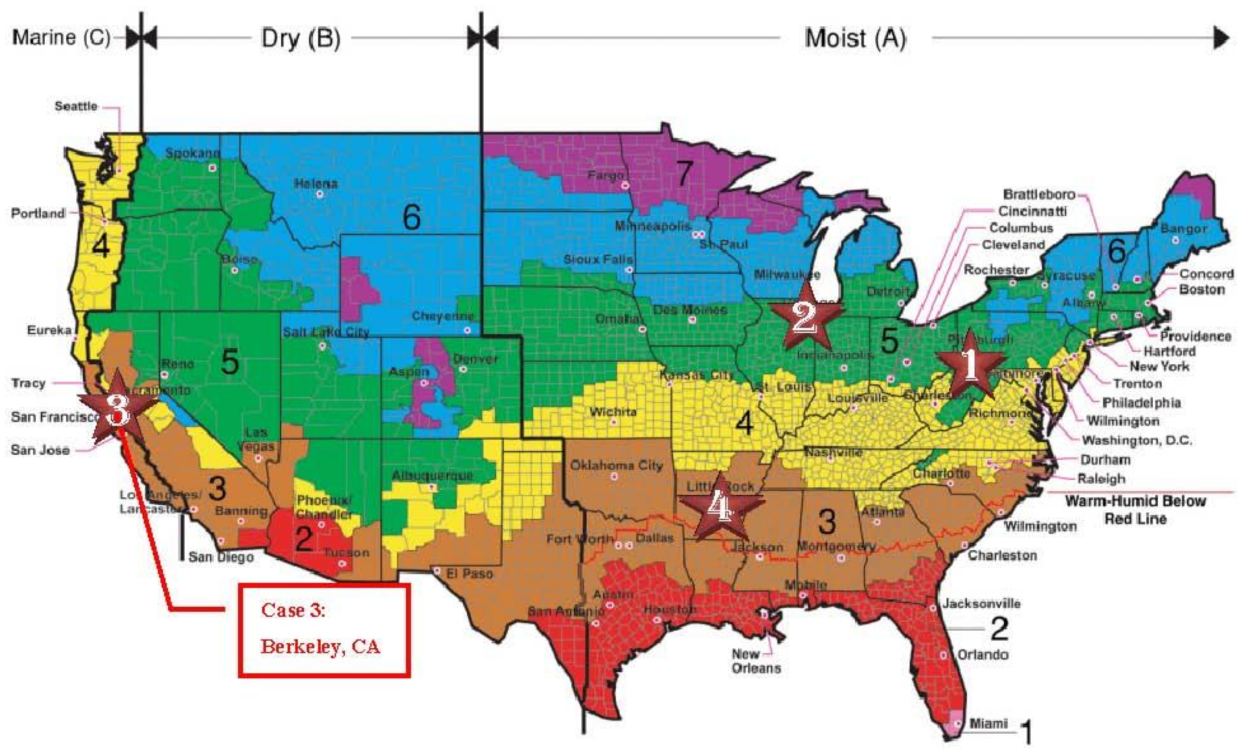


Figure 3.61. The location of case no. 3 in the climate zone map of the United States Source: (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010)

According to Figure 3.61 Berkeley is located in a warm-marine climate zone, which is defined as the "region that meets all of the following criteria:

a) A coldest month mean temperature between 27°F and 65°F

b) A warmest month mean of less than 72°F

c) At least 4 months with mean temperatures higher than 50°F

d) A dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere" (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010).

According to the Köppen climate classification, Berkeley has a Mediterranean climate, with warm to hot, dry summers and mild to cool, wet winters. Table 3.6 summarizes the average weather data for Berkeley, CA.

Table 3.6. Climate data (Average weather) for Berkeley, CA [1]
Source: (World Climate 2007; Software 2011)

Statistic	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Minimum Temperature	°F	43.6	46.1	47.4	48.6	51.3	53.6	55.1	55.7	55.9	53.5	47.9	43.7	50.20
Maximum Temperature	°F	56.4	59.3	60.9	64	66.6	69.5	70.4	70.6	71.7	70	62.3	56.6	64.86
Heating Degree Days (65 °F base)		491	374	354	287	210	129	104	97	100	170	317	492	Total 3125
Cooling Degree Days (65 °F base)		2	1	8	18	36	60	66	71	96	53	14	0	Total 425

[1] HDD and CDD were generated using Degree Days.net software. The numbers shown in the table are the average for the years 2006-2010 for the weather station located in Oakland Airport, CA.

3.2.4.10 Space function

The building includes a restaurant, meeting rooms, a theater, and office spaces. Due to the slow response of the radiant slab system, spaces with variable occupancy such as the theater, restaurant, and meeting rooms are located in the ground floor which has no radiant slab system, and all heating and cooling needs are met by high efficiency water heat pump HVAC systems (Integral Group 2011; Rumsey and Weale 2011).

3.2.4.11 Space characteristics

The building in general has a narrow plan to enhance natural ventilation and daylighting. From the photos and the building section, the ceiling height seems normal for an office building with the exception of the ground floor which is almost 1.5 of the normal height. Windows are located all around the building parameter. The ceiling surfaces of the slabs are left exposed, where the raised floors are covered with 100% nontoxic material (Rumsey and Weale 2011).

3.2.4.12 Construction system type

The slabs and the columns are all concrete (Miazga 2011).

3.2.4.13 Envelope configuration

In general, the envelope was designed to minimize the external loads while providing daylighting and natural ventilation to the interior. The roof has an R-value of 30.3 $h \cdot ft^2 \cdot °F/Btu$, where the metal frame walls have an overall R-value of 15 $h \cdot ft^2 \cdot °F/Btu$. The building envelope has a window to wall ratio of 20% with total U-value of 0.425 $BTU/(h\ °F\ ft^2)$. All the perimeter windows (except on the ground floor) are operable as are the skylights on the top floor (Rumsey and Weale 2011).

3.2.4.14 Heating, cooling, and ventilation

The building was designed to be naturally ventilated. The narrow plan and the operable windows helped in achieving this goal. For ventilation purposes, the building uses Dedicated Outdoor Air Systems (DOAS) which could provide 100% outdoor air without any re-circulated air. This DOAS operates to provide fresh air to the office spaces through the raised floor system during operation hours. During warm weather, the DOAS helps pre-cool the building's structure by flushing cool outdoor air through the building at night. The DOAS is connected to CO_2 sensors, to control the supply air of ventilation air whenever the sensors indicated high levels of CO_2.

The building cooling loads are met through evaporative cooling towers. Also, the building has a small compressor-based cooling system in selected gathering rooms such as the auditorium and the meeting rooms.

The temperature set-point is 70 F during winter and 78 F during summer. This could be achieved without the use of a compressor-based system in the office spaces (Rumsey and Weale 2011; Miazga 2011; Integral Group 2011).

3.2.4.15 Energy use

The building was predicted to use less than 40% of energy compared to similar U.S buildings. A night pre-cooling strategy decreases the peak electricity usage. The building produces about 66 kW of energy through its onsite PV system (Rumsey and Weale 2011).

3.2.4.16 Lighting

Through the use of external shading devices, light shelves, and narrow plan the building achieved nearly 100% daylighting. Dimming and occupancy sensors are used to minimize the use of the artificial lighting system (Rumsey and Weale 2011).

3.2.4.17 Additional points

At the beginning of the building's occupancy and during the cooling mode, the radiant slab had a night set temperature of 65 °F, so when people walked into the rooms in the morning they felt too cool and tended to turn on the heat. With this operation it would take the whole day to achieve the desire temperature. To eliminate this problem, the night set-point temperature was raised to 70 °F.

The cooling tower uses indirect evaporative cooling to provide the needed chilled water for the radiant slab system during summer. In winter high efficiency condenser boilers are used to provide hot water.

High-slag concrete was used in the foundation which reduced the use of cement by 70% and by 50% in the building structure (Rumsey and Weale 2011; Miazga 2011; Integral Group 2011)

Figure 3.62. David Brower center
Source: (Daniel Solomon Design Partners 2011)

Figure 3.63. (Left) ground floor plan. (Right) Second floor plan
Source: (Daniel Solomon Design Partners 2011)

Figure 3.64. Section showing integrated design strategy including the use of chilled slab system
Source: (Daniel Solomon Design Partners 2011)

Figure 3.65. Ceilings are left exposed for better heat exchange
Source: (Daniel Solomon Design Partners 2011)

3.2.5 Case Four: William J. Clinton Presidential Center, Little Rock, Arkansas

3.2.5.1 Building description

The building is partially elevated and takes the form of a glass bridge to symbolize President Clinton's theme of (Building a bridge to the 21st century). The building has a total area of 150,000 ft², where 70% is new construction and 21% is renovated. The building is divided into an 80,000 ft² exhibition (library and Museum) and 70,000 ft² archived section. The new construction is Silver LEED certified and the renovated section has a Platinum LEED certification. The center was completed in November 2004 (The American Institute of Architects 2007).

3.2.5.2 Radiant system

The building has an active slab system for radiant heating and cooling. The system is implemented only in the exhibition portion of the building which has the library, museum, and multipurpose hall. The floor surfaces of radiant floor system is the active side (The American Institute of Architects 2007).

3.2.5.3 System cooling capacity

No available information.

3.2.5.4 System surface temperature

No available information.

3.2.5.5 System control

The building systems are controlled by a Building Management System (BMS). The occupants have the ability to override and control their environment in certain areas such as the administrative offices. The exhibition wing is zoned separately to allow different operating modes (Pomerantz 2005).

3.2.5.6 System physical properties

The radiant system covers the majority of the exhibition area wing, around 55,000 ft^2. The floor is partially covered by tiles (areas with direct sunlight) and other parts have bamboo flooring (Pomerantz 2005; Macaulay 2010).

3.2.5.7 Designers' and clients' goals and preference

According to the architect, Richard Olcott, the building was designed to exemplify various sustainable design strategies while reflecting the Clinton's administration's commitment to the environment (U.S. Department of Energy 2007).

3.2.5.8 Codes and Standards

The building was built and designed according to the American building codes and standards. In addition, as a presidential library, the building has to meet "operational and redundancy standards of the U.S. National Archives and Records Administration. These guidelines are specific and demanding with respect to control of temperature, humidity, and gaseous contaminants within the various spaces in a facility of this type" (Pomerantz 2005).

3.2.5.9 Climate (Outdoor environment)

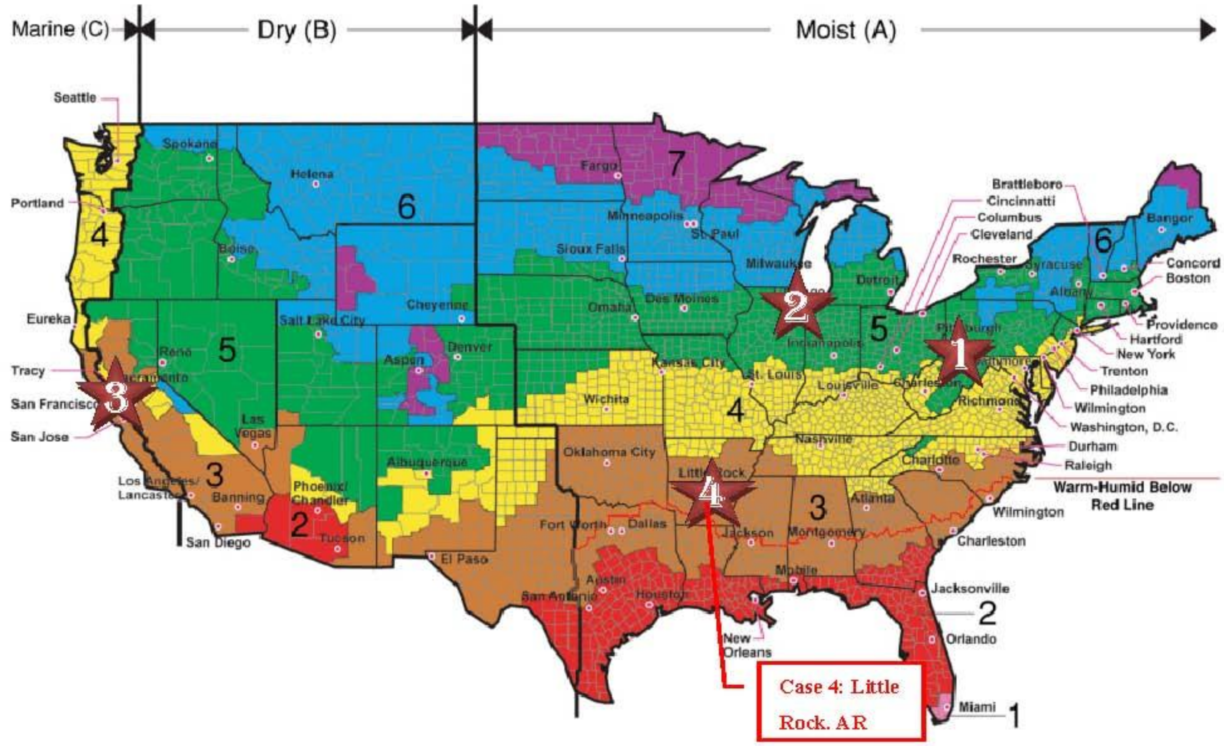


Figure 3.66. The location of case no. 4 in the climate zone map of the United States Source: (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010)

According to Figure 3.66 Little Rock is located in a warm-humid climate zone, which is defined as “ a region that receives more than 20 inches of annual precipitation, has approximately 5,400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 45°F during the winter months” (Pacific Northwest National Laboratory and Oak Ridge National Laboratory 2010). According to the Köppen climate classification, Little Rock has a humid subtropical climate, which is hot and humid in summers and mild in winters. Table 3.7 summarizes the average weather date for Little Rock, AR.

Table 3.7. Climate data (Average weather) for Little Rock, AR [1]
Source: (World Climate 2007; Software 2011)

Statistic	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Minimum Temperature	°F	30.8	34.8	42.6	50	59.2	67.8	72	70.5	63.6	51.5	41.5	33.9	51.52
Maximum Temperature	°F	49.5	55.6	64.2	72.9	81	89	92.8	92.1	85.1	75.1	62	52.5	72.65
Heating Degree Days		703	603	337	164	39	2	0	1	22	174	372	671	Total 3088
Cooling Degree Days		5	10	59	116	256	487	548	581	326	122	31	6	Total 2556

3.2.5.10 Space function

The bridge building has a wall exhibition, 220 seat multipurpose hall, 100 seat restaurant, 80 seat theater, gift shop, and education and media center. The exhibition and the library have approximately 3,500 visitors per week where each visitor spends around four hours (Macaulay 2010).

3.2.5.11 Space characteristics

The exhibition which is located in the bridge building has a total length of 240 ft and a width of 40 ft with 32 ft ceiling height. The building's facades are fully glazed (The Green Building Initiative 2008).

3.2.5.12 Construction system type

The building structural system is a mixture of onsite cast concrete, precast concrete, steel, and glazed wall system.

3.2.5.13 Envelope configuration

The envelope was designed to allow outdoor views and enhance daylight utilization while minimizing the solar loads. The primary material of the bridge building envelope is low-iron

[1] HDD and CDD were generated using Degree Days.net software. The numbers shown in the table are the average for the years 2006-2010 for the weather station located in Adams Field Airport, AR.

insulated glass which allows natural daylighting and absorbs some of the sun's heat. The western side of the building has a double envelope wall with a secondary glass wall across an adjacent exterior walkway which in total reduce the sun's energy by 55% (BuldingGreen.com 2007). The heat absorbed by the double envelope wall system is vented through louvered elements in the top of the wall.

Solar shading devices are automatically controlled and operated to minimize solar gain. The roof, which is shaded by the photovoltaic panels, has a value of R-30 $h \cdot ft^2 \cdot °F/Btu$, and the gravel covering the roof is painted white to improve sun reflectivity. (U.S. Department of Energy 2007; Macaulay 2010)

3.2.5.14 Heating, cooling, and ventilation

The displacement system provides cooling and the needed air for ventilation. Also with the help of the radiant cooling floors the system creates temperature stratification helping keep the occupied zone within the comfort zone. This also ensures clean air in the occupied zone by providing continuously fresh air. Ventilation is supplied on demand as determined by the CO_2 sensors (BuldingGreen.com 2007).

3.2.5.15 Energy use

Through different design strategies and the use of energy efficient systems the building uses 25% less energy when compared to a typical code-compliant building. The building produces 60 kW of power through the photovoltaic panels installed on the roof (BuldingGreen.com 2007)

The Building Management System (BMS) tracks energy use by specific area, with sub-metering of major energy uses (U.S. Department of Energy 2007).

3.2.5.16 Lighting

Daylighting was optimized through the building orientation and window-to-wall size ratio. 80% of the building has direct ambient daylight with a daylight factor of 0.2-0.5 (Green Building Initiative 2011). Solar shading devices can be overridden by occupants to control brightness and glare from direct sun (Macaulay 2010).

3.2.5.17 Additional points

The building staff are trained and educated concerning how to use and maintain the building and its systems. (U.S. Department of Energy 2007; Macaulay 2010)

Figure 3.67. The William J. Clinton Presidential Center
Source:(The American Institute of Architects 2007)

Figure 3.68. The bridge building of William J. Clinton Presidential Center
Source: (newyork-architects.com 2011)

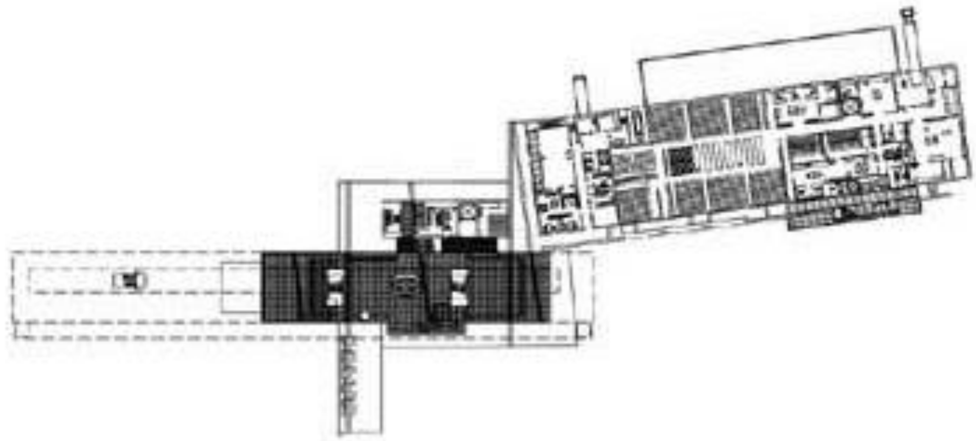


Figure 3.69. Ground floor plan of the William J. Clinton Presidential Center, the bridge building is on the left.
Source: (moreAEdesign 2010)

Figure 3.70. Section through the bridge building
Source: (Glasser 2002)

Figure 3.71. Inside the bridge building of the William J. Clinton Presidential Center
Source: (moreAEdesign 2010)

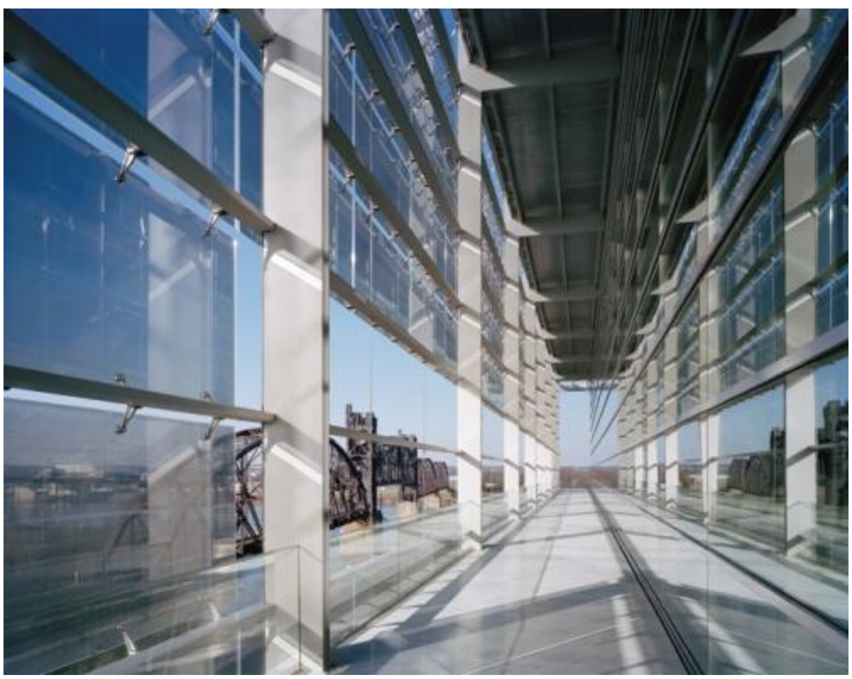


Figure 3.72. The envelope system of the western façade of the bridge building
Source: (moreAEdesign 2010)

3.2.6 Case Five: Suvarnabhumi Airport, the New Bangkok International Airport, Bangkok, Thailand

3.2.6.1 Building description

The 4,036,000 ft^2 building is the 3rd largest single-building airport terminal in the world. The airport is one of the busiest airports in Asia as passengers and air cargo move 24 hours a day. The building was completed in 2006 (Jardine Engineering Corporation 2007).

3.2.6.2 Radiant system

The building uses a chilled slab system as one of the major mechanical cooling systems. As of 2006, it is the largest chilled slab system in the world, with coverage area of 1,087,000 ft^2, and 372.8 miles of embedded tubes in the slabs. The tubes were laid with 6 inches of spacing between their centers in the sunny areas and 7.8 inches in the shaded areas. Tubes were covered with 2.7 inches of concrete and the ground floors have 4 inches of insulation underneath (Kessling, Holst, and Schuler 2004).

3.2.6.3 System cooling capacity

The system is designed for maximum cooling capacity of 25 Btu/ h•ft^2 (80 W/m^2). However, in some areas the system cooling capacity could reach 27 Btu/ h•ft^2 (85 W/m^2) (Kessling, Holst, and Schuler 2004).

3.2.6.4 System surface temperature

The system was designed to have a permanent inlet water temperature of 55 °F. That would keep the surface temperature at 71.6 °F during the day and 66.2 °F at night. The return water temperature is 66.2 °F (Kessling, Holst, and Schuler 2004).

3.2.6.5 System control

The system was designed with 7,500 chilled slab circuits for maintenance, control, and operation. The system surface temperature is always 2 °F above the ambient dew-point temperature. The indoor RH is kept between 50% to 60% (Kessling, Holst, and Schuler 2004).

3.2.6.6 System physical properties

The system covers about one third of the airport floors (terminal building and the concourses). The main concourse building has a total length of 11,500 ft with 150 ft width. The floors appear from the photos to have a finishing material of tiles and they have bright colors (Kessling, Holst, and Schuler 2004).

3.2.6.7 Designers' and clients' goals and preference

According to the architect, Helmut Jahn, the goal was "to develop an optimized building concept in a design team comprising the architects, structural and mechanical engineers, HVAC, acoustic, and climate engineers" (Kessling, Holst, and Schuler 2004). From thermal comfort point of view, the idea was to create an indoor climate conditions with operative temperature of 75 °F and 50% to 60% RH (Kessling, Holst, and Schuler 2004).

3.2.6.8 Codes and Standards

The building was built and designed according to the Thai building codes and standards.

3.2.6.9 Climate (Outdoor environment)

According to the Köppen climate classification Bangkok has a tropical wet and dry climate, with average temperatures of 77 °F to 90 °F and high relative humidity all around the year. Table 3.8 summarizes the average weather data for Bangkok.

Table 3.8. Climate data (Average weather) for Bangkok [1]
Source:(World Climate 2007; Software 2011)

Statistic	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Temperature Mean Value	F	78.6	81.3	83.7	85.5	84.6	83.7	82.9	82.6	82	81.7	80.4	78.1	82.1
High Temperature Mean Daily Value	F	89.6	90.9	92.7	94.8	93.2	91.6	90.9	90.5	90.1	89.6	88.9	88.3	90.9
Low Temperature Mean Daily Value	F	69.8	73.9	76.8	79	78.1	77.7	77	76.8	76.3	75.7	73.6	69.4	75.3
Heating Degree Days (65 °F base)		2	0	0	0	0	0	0	0	0	0	0	0	Total 2
Cooling Degree Days (65 °F base)		468	526	565	683	633	606	593	597	575	560	497	488	Total 6864

3.2.6.10 Space function

The airport operates 24 hours a day, 7 days a week. The airport has many facilities and activities with average cooling loads demand of 43 Btu/ h•ft² (135 W/m²) (Kessling, Holst, and Schuler 2004; Somcharoenwattana et al. 2004).

3.2.6.11 Space characteristics

There are two building prototypes in the airport; the main terminal building, and the concourse buildings. The main terminal building measures 1,450 ft by 360 ft. The concourse buildings have a total length of 11,500 ft with 150 ft in width. The building envelope was designed to maximize the natural light intrusion while minimizing the outdoor heat transfer. At the eye level in both buildings, occupants can see outdoors continuously through clear glass (Kessling, Holst, and Schuler 2004).

[1] HDD and CDD were generated using Degree Days.net software. The numbers shown in the table are the average for the years 2006-2010 for the weather station located in Bangkok International Airport, Bangkok.

3.2.6.12 Construction system type

In general, the construction system could be described as high-tech construction. The main components are steel frames, tensile structures, and concrete floors and bridges to the inside.

3.2.6.13 Envelope configuration

New materials were developed to form the airport envelope to create optimal thermal, visual, and acoustical indoor environments while creating a highly transparent building and to minimize the energy consumption. In the terminal building, the idea was to separate the weather and sun protection layers from the building structure.

In the concourse buildings, the envelope was constructed using two different groups of materials; transparent glass façade for a outside view, and translucent roof membrane to enhance daylighting. Both groups of materials were carefully design to reduce heat gain through the envelope. The concourse envelope was designed to absorb sounds from the outside and from the inside.

The glazed part used glass with different values of transmission, reflection, and absorption of solar radiation and daylight depending on their location on the envelope. The membrane used translucent materials that would diffuse the sunlight while keeping most of the heat out (Kessling, Holst, and Schuler 2004).

3.2.6.14 Heating, cooling, and ventilation

To avoid cooling the entire large volumes of air in the airport and to minimize the need for cool air, the airport interior was divided horizontally into two zones: the cooled and conditioned zone 8 ft above the occupied floors, and the unconditioned zone at higher levels. This thermal stratification was maintained by using radiant chilled floor systems and displacement ventilation. The operative temperature in the conditioned spaces maintained at around 80 °F during the day and slightly below the ambient temperature during the night, while the air temperature in the unconditioned spaces could reach the ambient air temperature during the day.

A displacement ventilation system was used for cooling and ventilation. This system is used for cooling, ventilation, and dehumidification purposes. This system supplies cooled air with a temperature of 65 °F to the space at floor level at low velocity. This system also insures the thermal stratification in airport space where the conditioned zone is limited to the air volume 8 ft above the floor in each occupied space. This strategy reduces the amount of conditioned air needed and thus reduces the cooling loads and the need for high thermal insulation in the building envelope (Kessling, Holst, and Schuler 2004; Somcharoenwattana et al. 2004).

3.2.6.15 Energy use

The integrated design approach, the optimization of the building envelope, and the combined cooling approach helped in reducing the annual energy demand from 191GWh to 107GWh (about 30%) (Kessling, Holst, and Schuler 2004; Somcharoenwattana et al. 2004).

3.2.6.16 Lighting

Enhancing the daylight inside the airport building was a main design goal, as this was expected to enrich the aesthetic value of the interior and reduce the use of artificial lights and thus reduce the total cooling load. In the terminal building, large canopies were used to shade the building while allowing daylight penetration. In the concourse buildings, the extensive use of glass and the translucent membrane helped eliminate the use of artificial lights during the day even with overcast skies (Kessling, Holst, and Schuler 2004).

3.2.6.17 Additional points

Most of the companies that participated in the construction of this airport tested their products in use before being implemented. This was due to the unconventional materials used in the envelope and due to the large area of the airport (Kessling, Holst, and Schuler 2004).

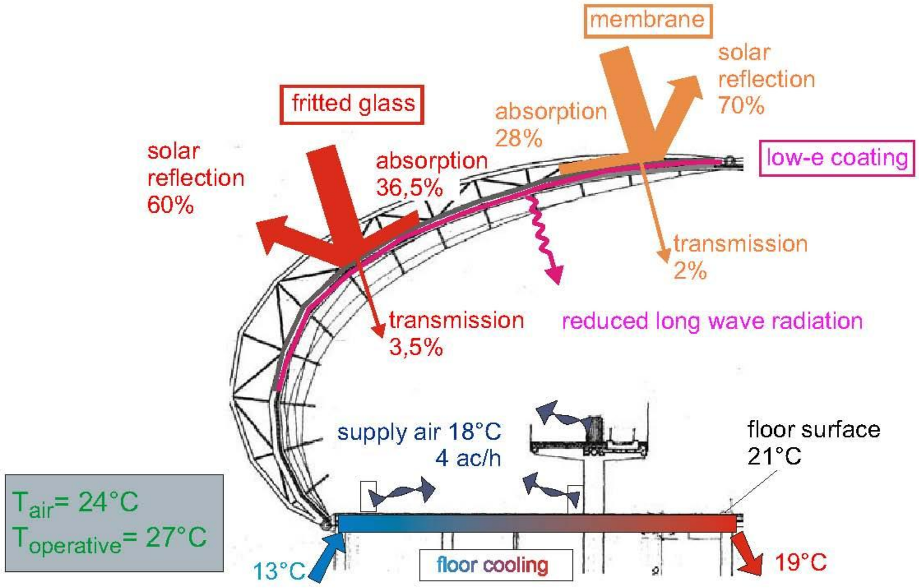


Figure 3.73. Climate control strategies in the concourse areas
Source: (Kessling, Holst, and Schuler 2004)

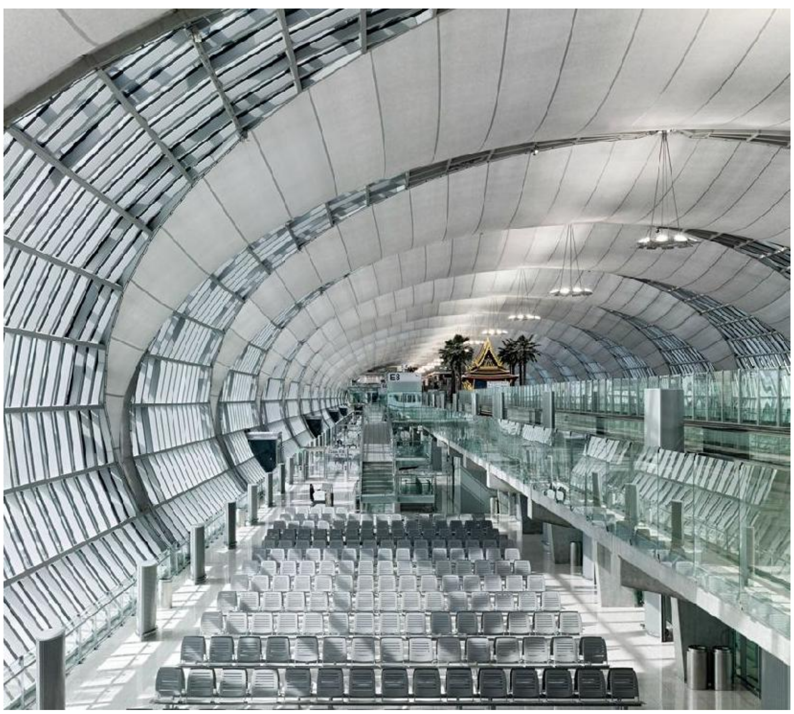


Figure 3.74. Inside a typical concourse building, where the transparent glass and the translucent membrane are alternating in the envelope perimeter
Source: (Murphy/Jahn Inc. 2007)

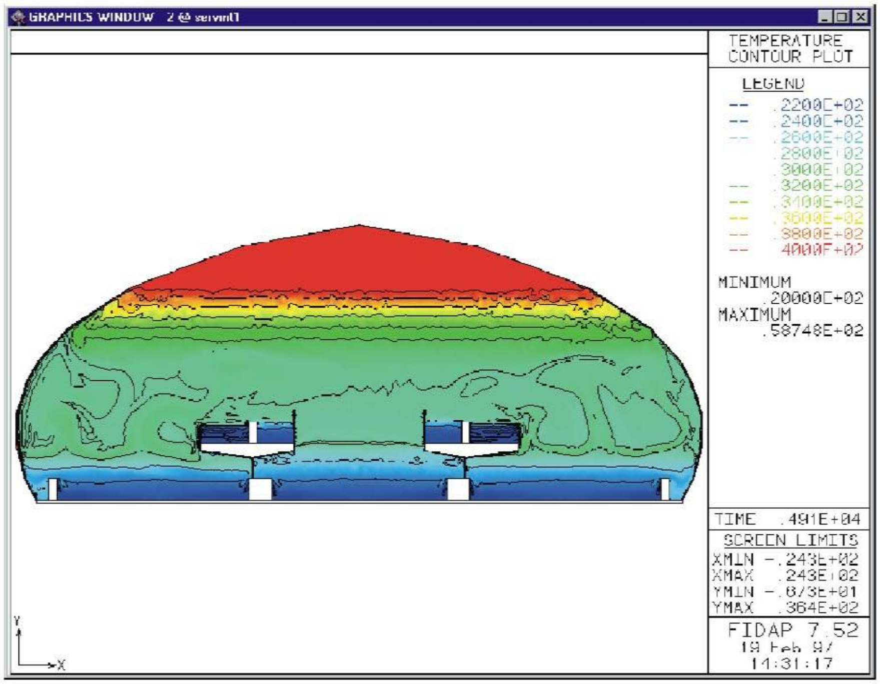


Figure 3.75. Energy simulation of the thermal stratification concept
Source: (Kessling, Holst, and Schuler 2004)

Figure 3.76. Chilled slab system in construction
Source: (Murphy/Jahn Inc. 2007)

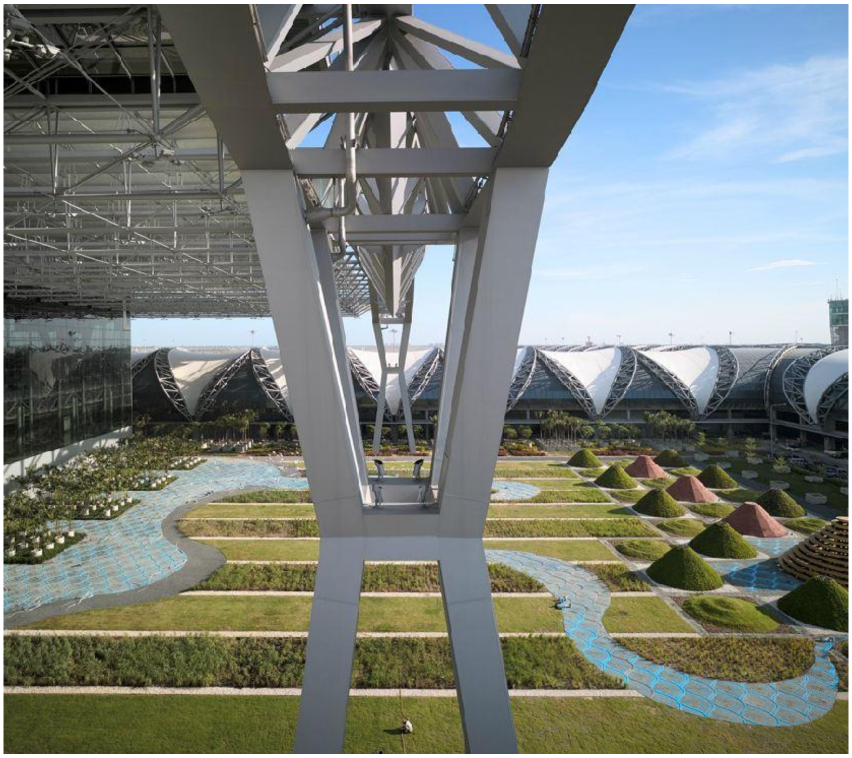


Figure 3.77. Concourse buildings
Source: (Murphy/Jahn Inc. 2007)

Figure 3.78. Terminal and concourse buildings
Source: (Murphy/Jahn Inc. 2007)

3.2.7 Case study findings

3.2.7.1 RC system cooling capacity

To meet the space cooling loads the RC systems were combined with another cooling system or strategy such as displacement or natural ventilation. The combined system/strategy was mainly to provide the needed air for ventilation and take care of the latent cooling loads. Designers used these ventilation systems/strategies in addition to the RC system to match the space cooling loads.

In case two (library), the RC system was designed to meet 60% of the sensible cooling loads, where the displacement ventilation system or natural ventilation was used to meet the other cooling loads. In case three (Brower center), natural ventilation was used along with RC systems to meet the cooling loads of building.

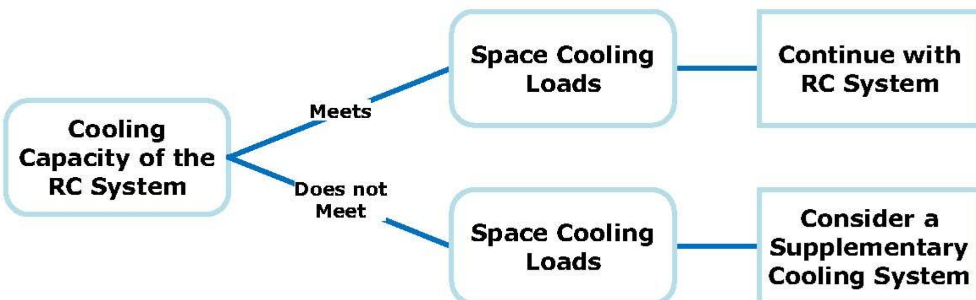


Figure 3.79. Space cooling loads and RC cooling capacity relation (decision tree)

Although all the case studies have chilled slab systems, the RC system cooling capacity differs from case to case based on: space function, active surfaces of the RC system (ceiling surfaces or/and floor surfaces), and envelope configuration.

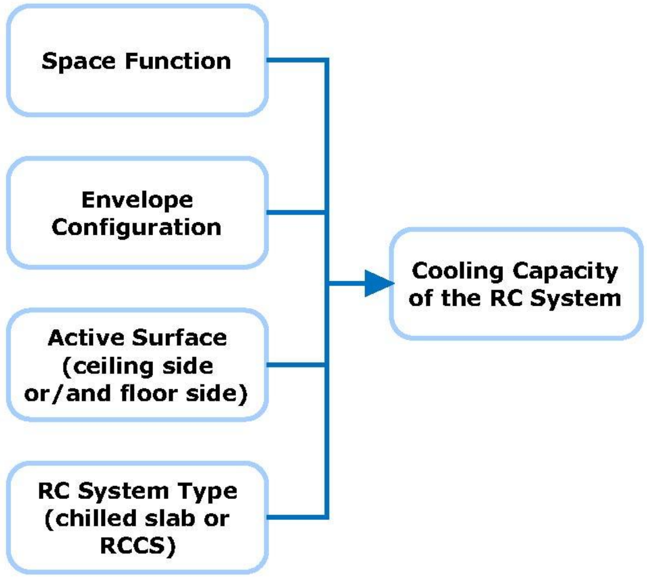


Figure 3.80. Some of the variables affecting the RC system cooling capacity

In all cases, the envelope system was designed in a way to minimize the external heat gain so the RC system cooling capacity could match the space cooling loads.

In case one (yoga center), the external shading devices were used. In case two (library), the western façade has a double envelope system. In case three (Brower center), external shading devices were used to minimize solar heat gain. In case four (museum), the western side of the building has a double envelope wall with secondary glass wall. Case five (airport) was an exception due to the huge area of the envelope system.

Figure 3.81. Envelope configuration and RC system cooling capacity relation

No specific details in regard to the heat exchange with the cooled surfaces were noted. However, the different configuration of each case suggests different heat exchange values. In case one (yoga center), the ceiling sides and the floor sides are uncovered and radiant cooling and heating occurs in both sides. In case two (library), the ceiling vaults are to increase the effective surface area of the radiant heat transfer of the ceiling sides. In case three (Brower center), the ceiling sides are the active sides and they are left uncovered. In case four (museum) the radiant system was implemented in the exhibition so the floor side is the active side, part of the floor was uncovered and some parts were covered by a wood floor. In case five (airport), the RC system was designed to have a cooling capacity of 25 Btu/ h•ft² in most areas, and 27 Btu/ h•ft² in areas receiving direct sun.

In conclusion, the RC system cooling capacity should not necessarily match the space cooling loads alone, other systems/strategies may be used to help meet the space sensible cooling load and to take care of the latent heat load.

3.2.7.2 RC system surface temperature

In all cases, the system surface temperature was set and controlled by an automated Building Management System (BMS) to keep its temperature above the indoor air dew point temperature all the time and to keep the space within the thermal comfort zone.

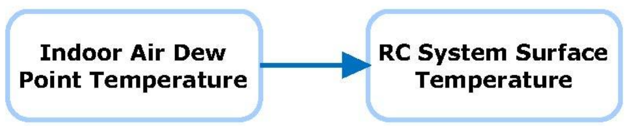


Figure 3.82. Indoor dew-point temperature and RC system surface temperature relation

In case three (Brower center) the system surface temperature was set to be all the time at 70 °F during the cooling season. However, in case five (airport) the system surface temperature was reset from 66.2 °F during the day to 71.6 °F at night in response to the changes in the sensible cooling load coming from the solar radiation.

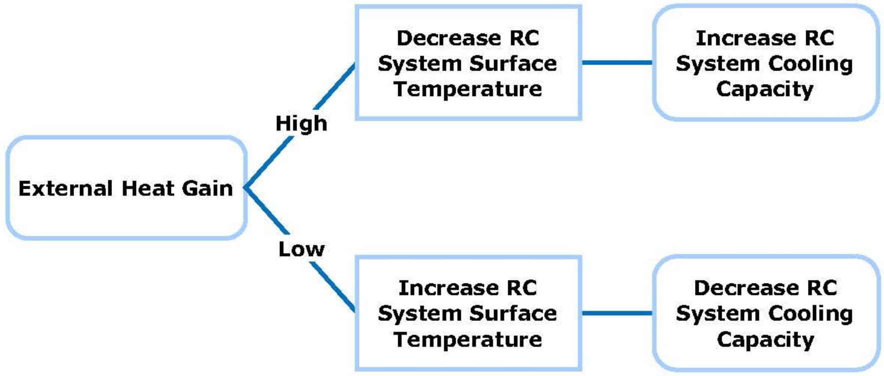


Figure 3.83. External heat gain and RC system cooling capacity relation (decision tree)

In case one (Yoga center), the system was not installed in the slab of the ground floor as in the other five floors, because occupants are expected to be there with bare feet during yoga classes.

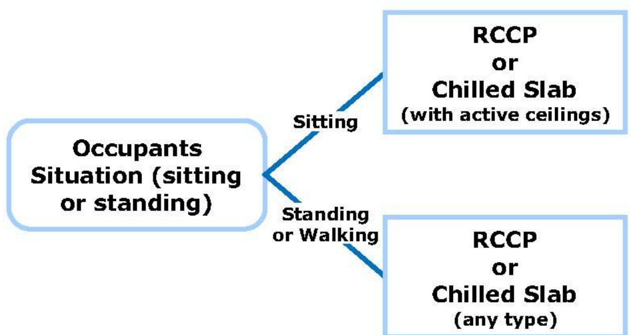


Figure 3.84. Occupancy situation may affect the RC system chosen (decision tree)

3.2.7.3 RC system physical properties

The RC system occupied a high percentage of the ceiling and/or floor area of the spaces where it was installed. In case two (library) the RC system covers about 80% of the ceiling area where the system was installed. In case three (Brower center) the system covers the whole ceiling area, and in case four (museum) the system covers most of the floor area in the bridge building especially in the areas which are exposed to direct sun. These differences are related to different cooling loads the spaces have.

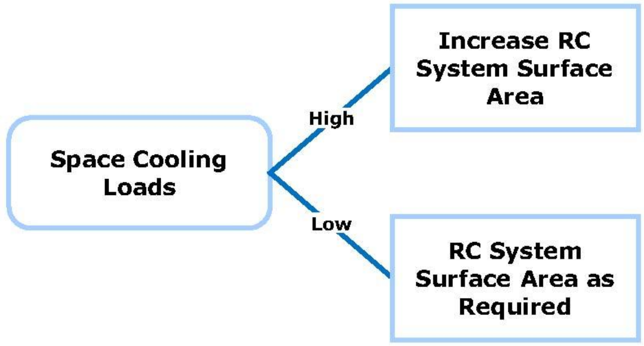


Figure 3.85. The physical dimensions of the RC system effect in the system cooling capacity (decision tree)

It was noticed that the implementation of the RC system was used in conjunction with a raised floor system to accommodate the ventilation systems and any other system as in case two (library) and case three (Brower center). Mounting heavier systems such as the mechanical system in the ceiling where the radiant system was installed was avoided, although lighter systems such as lighting fixtures were mounted.

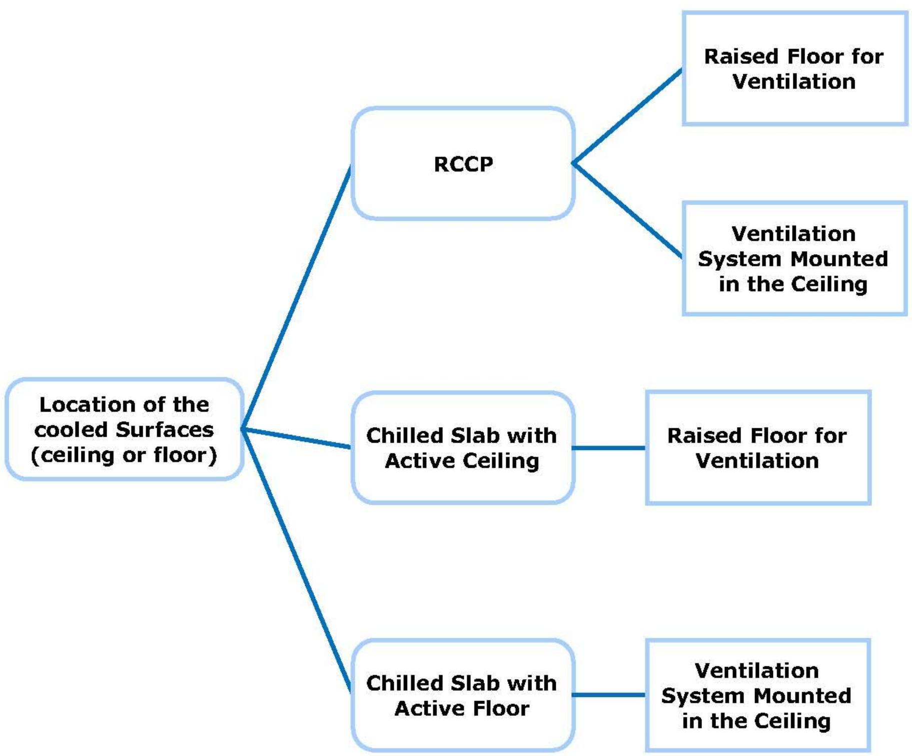


Figure 3.86. The RC system location may affect the implementation of other system in the same space such as the ventilation system (decision tree)

In case one (Yoga center), case two (library), and case three (Brower center) the radiant system finishing material was concrete that was left exposed to the conditioned space for better heat exchange. The exposed concrete was painted as in case two (library) and as in case three (Brower center) or left to its natural color as case one (Yoga center). In case four (museum) the floor was partially covered with bamboo flooring for aesthetic purposes, and it was not mentioned how that will affect the radiant heat exchange.

3.2.7.4 System control

In all cases, the building was thermally zoned to accommodate the different heating and cooling loads for different spaces. In case three (Brower center) the radiant system was designed with the ability to provide heating for one zone and cooling to another to create the desired thermal comfort environment and to reduce energy consumption.

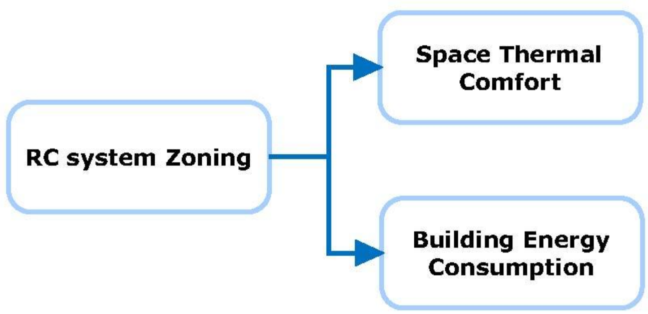


Figure 3.87. Zoning the RC system helps to provide better thermal comfort and reduce energy use

In case two (library), case three (Brower center), and case four (museum) the buildings were connected to a Building Management System (BMS). The BMS is mainly to control radiant system surface temperature, indoor RH, and the interior temperature set points. Controlling these variables will provide the desired thermal environment, and prevent system failure.

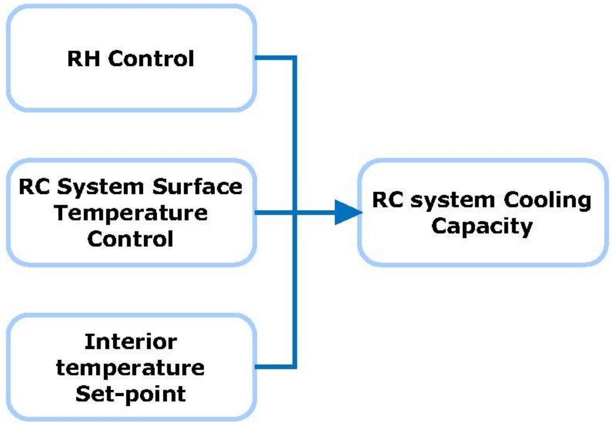


Figure 3.88. Variables which may affect the RC system cooling capacity

3.2.7.5 Designers' and clients' goals and preference

All cases shared a common goal: to design an energy efficient building using advanced technologies and systems. Many design strategies and systems were used to achieve this goal including radiant cooling/heating systems.

3.2.7.6 Building codes and Standards

The first four cases were built and designed according to the U.S building codes and standards, and the last case was built and designed according to the Thai building codes.

This means that there are no contradictions between the implementation of radiant system and codes and standards even though there are no specific codes for the use and implementation of RC systems in the U.S.

3.2.7.7 Climate (Outdoor environment)

Case one (Yoga center), case two (library), and case four (museum) are located in a hot and humid climate. Case five (airport) is located in a tropical climate, and case three (Brower center) is located in a Mediterranean climate. This reveals that the outdoor relative humidity and hot outside air temperature are not constraints to the implementation of RC systems. However, it did mean that the mechanical ventilation system had to care of the latent heat loads, as RC systems will typically only remove the sensible heat loads.

In all cases the buildings were designed to have a thermally efficient envelope system to minimize the solar heat gains, conduction heat gain, and infiltration, so the RC system cooling capacity could more easily match the space's sensible cooling load.

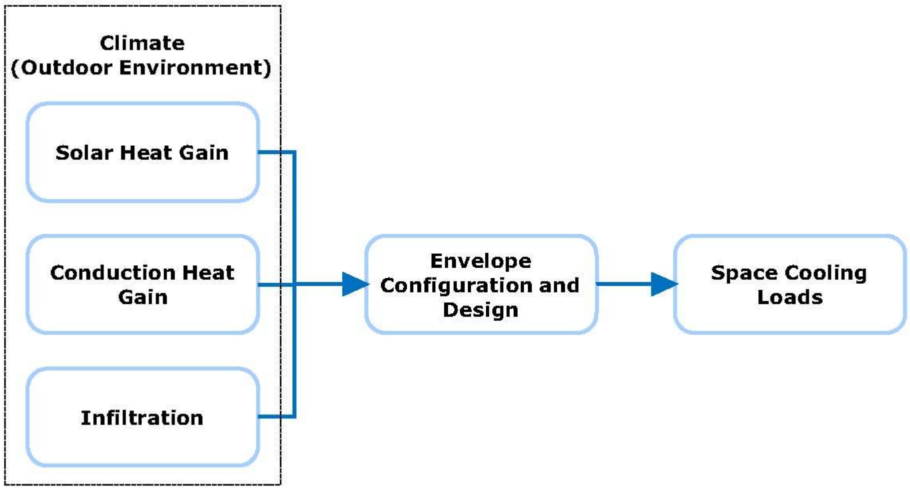


Figure 3.89. The relationship between the outdoor environment and the space cooling loads

In case one (Yoga center), case two (library), and case three (Brower center) natural ventilation was used through automated or manually operable windows. Natural ventilation was used only when the outdoor weather conditions permit.

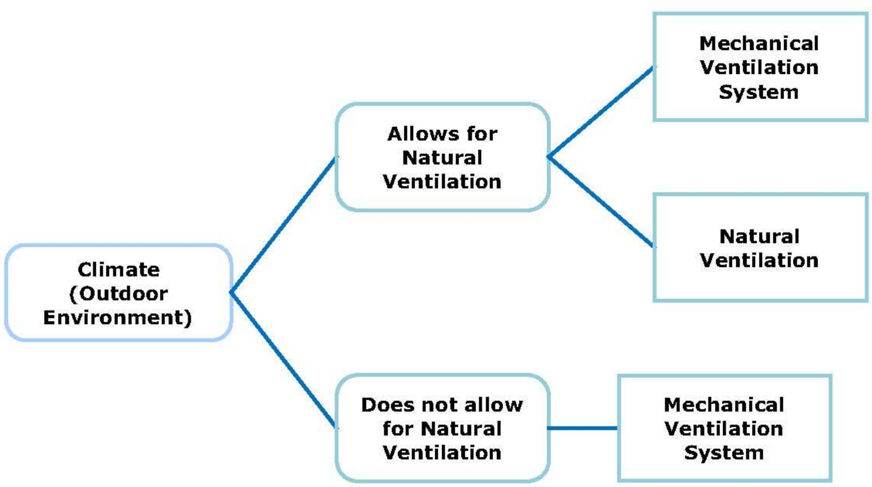


Figure 3.90. The outdoor environment affects the selection of the ventilation strategy (decision tree)

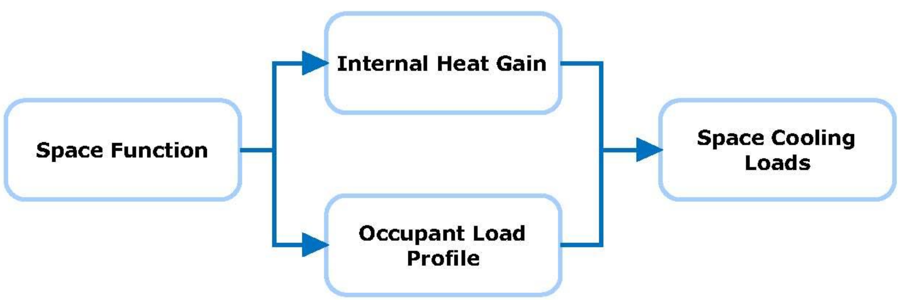
3.2.7.8 Space function

In spaces with steady heating and cooling loads the RC system output was enough to meet the sensible cooling load, while an additional mechanical system was installed for ventilation purposes.

In case one (yoga center) an additional cooling/heating system was installed in the guest rooms so each room could be individually controlled.

In high occupancy density spaces or in spaces with variable cooling loads such as restaurant, classroom, exhibition areas, and meeting room, theses spaces were grouped together and heated and cooled by conventional mechanical systems.

In case one (Yoga center), the multipurpose hall was located on the ground floor and supplemented with additional ventilation and humidity control systems. In case two (library), classrooms and seminar rooms at the bookends of the building have a separate VAV ceiling system to respond to the variable cooling loads that may happen there. In case three (Brower center) theater, restaurant, and meeting rooms are located in the ground floor which has no radiant slab system, and all heating and cooling needs are met by high efficiency water heat pump HVAC systems.



.

Figure 3.91. Space function and is a major variable when calculating space cooling loads

In all cases the radiant slab system was installed, which is typically slow to react to rapid changes in the load, and is suitable in spaces with steady cooling/heating loads. This may suggest that ceiling systems, with their generally quicker response times when compared to slab systems, may be preferable in dynamic loads spaces.

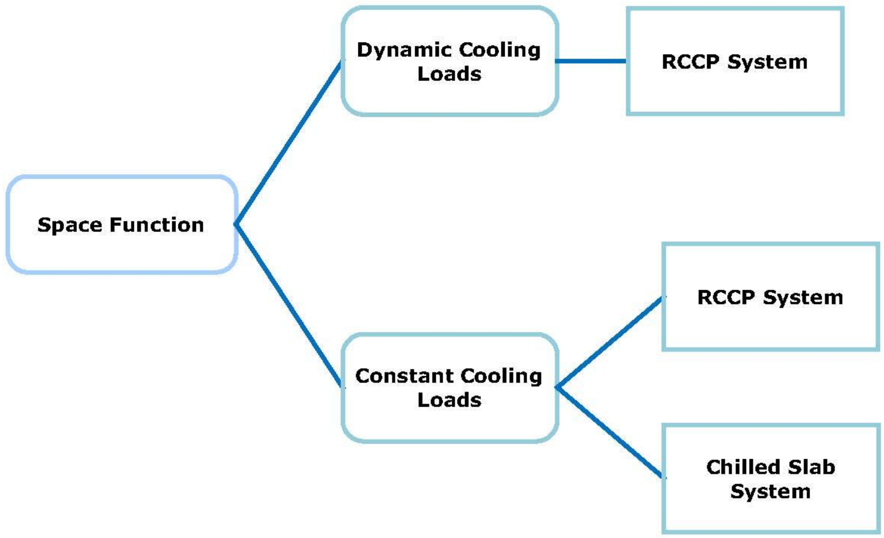


Figure 3.92. Space function affects the selection of the RC system type (decision tree)

In case four (museum) and in case five (airport) due to the nature of the space function and surrounding climate conditions natural ventilation was not an option. Therefore, mechanical ventilation was installed with the ability to provide cool dry air for ventilation and to help the RC system meet the space cooling loads.

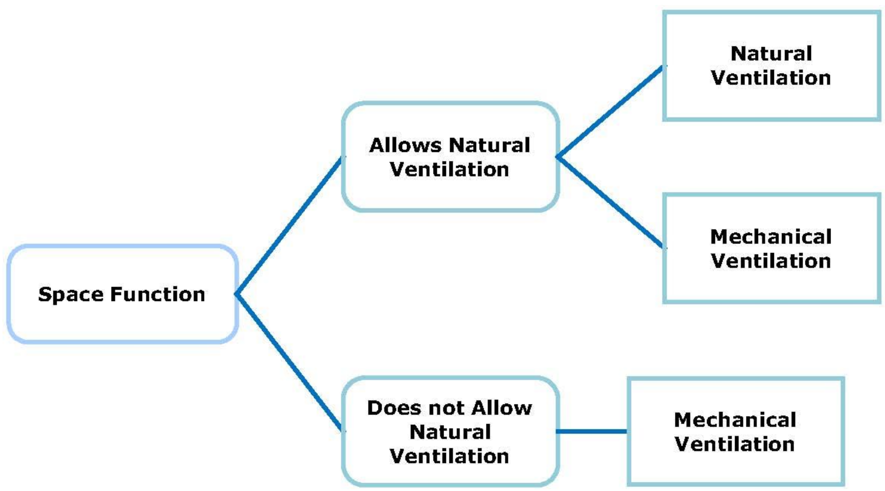


Figure 3.93. The ventilation strategy may be determined by the space function (decision tree)

3.2.7.9 Space characteristics

In case one (yoga center) and in case three (Brower center) the ceiling sides were the thermally active surfaces, therefore the ceiling height was 8 ft, and 9 ft respectively. However, for spaces having high ceilings as in case four (museum) and in case five (airport) the thermally active surface was the floor and not the ceiling. This is mainly due to the fact that the ceiling height and the value of the angle factor have inverse relationship. The values of the angle factor and the MRT have a proportional relationship. MRT calculation is discussed in details in sections 3.1.2.3.6 and 3.1.2.3.7.

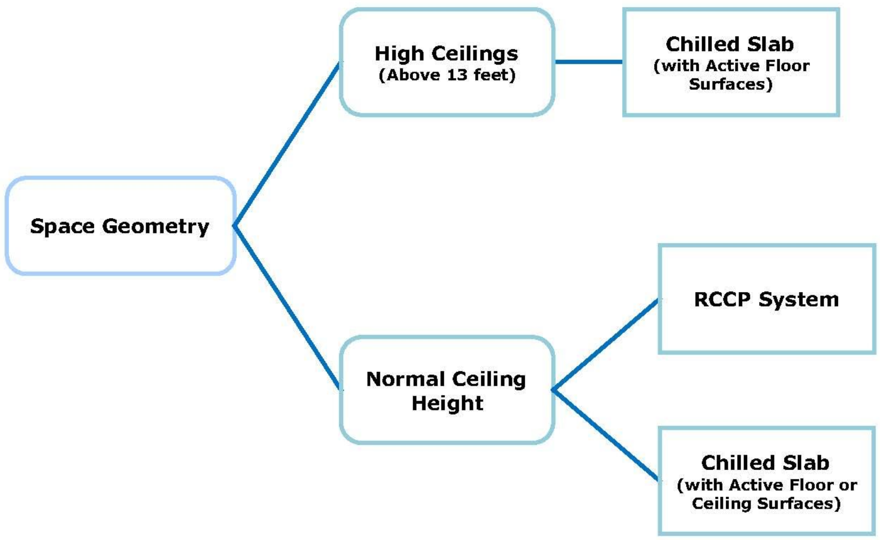


Figure 3.94. The space geometry affects the RC system selection (decision tree)

In all cases the radiant system finish material (concrete) was left exposed to the conditioned spaces for better heat exchange.

Figure 3.95. Finishing materials affect the RC system cooling capacity

It was expected that window placements and size are variables that could affect the decision to install a RC system. Case two (library), case four (museum), and case five (airport) show that the building could have a high percentage of glazed area in the envelope and still use a RC system.

3.2.7.10 Construction system type and envelope configuration

In all cases, the floors and ceiling which contained the radiant system were made of concrete. In case one (Yoga center), case two (library), and case three (Brower center) the active surfaces were the ceiling side, where in case four (museum) and case five (airport) the active surfaces were the floor side. If radiant ceiling panel systems were used, the ceilings and floors could be made of any conventional materials and systems.

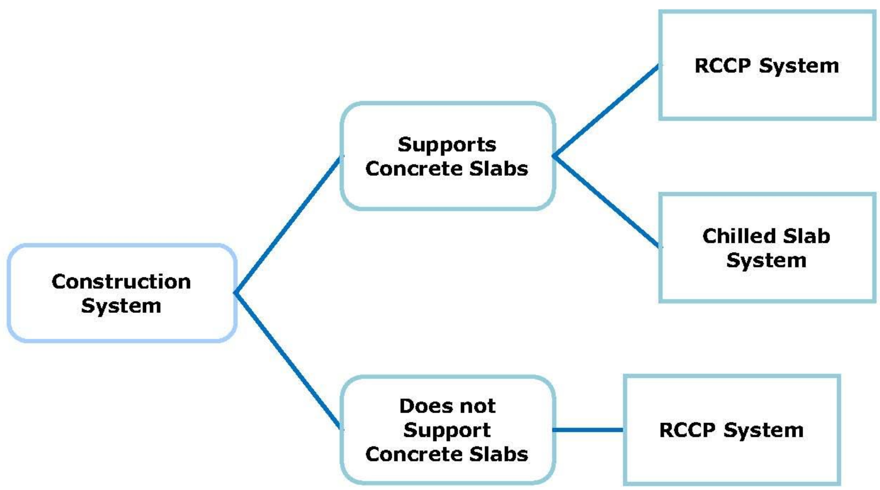


Figure 3.96. RC system type selection affected the construction system type (decision tree)

In the previous cases while all the floors and ceilings are constructed of concrete slab systems, there are many envelope configurations and systems. Case one (yoga center) has an envelope system with 30% of its area glazed and operable windows. For case two (library) more than 80% of the western and eastern facades are glazed with automated window openings. Case five (airport) the envelope system is constructed of tensile structures. In conclusion, radiant systems can be installed with any construction system type, but the envelope configuration (enclosure) must perform certain functions such as reducing solar heat gain to make the system work successfully.

3.2.7.11 Ventilation system

An RC system will remove directly the sensible heat load of the space, and indirectly some of the latent heat load. However, additional strategies or systems are needed in the conditioned space to provide ventilation and to take care of most of the latent heat loads. These strategies or systems could be natural ventilation, displacement ventilation, and mixed ventilation. For the mechanical systems the dedicated outdoor air approach could be used for better IAQ.

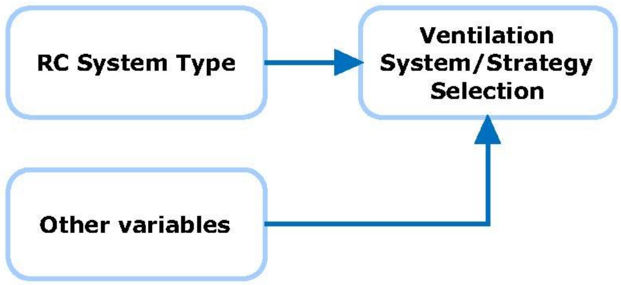


Figure 3.97. The ventilation strategy decision may be affected by the RC system type

In case one (yoga center) occupants could manually and individually open the windows to allow fresh air in. However, there is a mechanical ventilation system connected to each room to provide the needed air for ventilation when windows are closed or when the outdoor weather does not allow for natural ventilation.

In case two (library) the building could run in the ventilation mode when outdoor weather conditions allow, or could use the displacement ventilation to provide fresh air and remove latent heat.

In case three (Brower center) the building has a displacement ventilation system with dedicated outdoor air system (DOAS) which provides 100% outdoor air. The mechanical system is also used to flush and pre-cool the building during the night. The building has operable windows for natural ventilation controlled by occupants.

In case four (museum) the building has a displacement system for ventilation which helps creating thermal stratification.

In case five (airport) the building has a displacement ventilation system for cooling and ventilation purposes and to provide cool dry air to the spaces. The system also creates the horizontal thermal stratification to avoid cooling unoccupied spaces above 8 ft high.

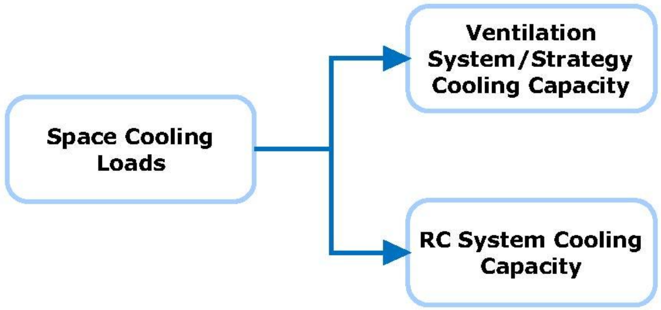


Figure 3.98. The ventilation strategy and RC system cooling capacity should match the space cooling loads for better thermal environment

In conclusion, natural ventilation or displacement ventilation with/without DOAS could be combined with the radiant slab system. Mixed ventilation was not an option due to the fact it needes to be mounted in the ceiling were the tubes are embedded. There is no obvious restriction or limitation for the selection of any ventilation system, it is a design decision made in conjunction with other variables such as space function, occupant load profile, standards and codes, and outdoor weather conditions.

3.2.7.12 Additional systems

Lighting system

All cases were designed to utilize daylight and to minimize the use of artificial light as much as possible. In case one (yoga center) the ceilings, which are the thermally active surfaces, were kept clear and uninterrupted. However, in case two (library) and case three (Brower center) the ceilings, which are also the thermally active surface, were designed to integrate the artificial lighting system. This means there is no conflict between having the lighting system in the ceiling and using it as the thermally active surface.

Fire suppression system

It was not mentioned in any of the cases if the fire suppression system could be integrated with the water loop of the radiant system. However, using the ceiling sides to be the thermally active surface did not conflict with the installation of the fire suppression system in the ceiling as in case one (yoga center) and in case two (library).

3.3 Sources of Relevant Knowledge: Interviews

The interviews are the third source of the relevant knowledge in this research as discussed previously in the research methodology. The information extracted from these interviews will influence the development of the framework by capturing the selection process and subjective decision-making process when designing RC systems. This section includes the findings of the interviews with the RC systems experts. The interview questions, see appendix A, were open-ended and designed to give the interviewees the ability to talk about their experiences with RC systems.

3.3.1 The interviews data processing

The grounded theory approach was used to analyze the collected interview data. The approach contained four main stages. The first stage was to identify and highlight the main ideas in each interview, and see the common concepts between the different interviewees. The second stage was to mark the key points with a series of codes to summarize the key characteristics of each interview. Then the codes with similar concepts were collected into groups; the relations between these groups were identified as each group has its own characteristics. The final stage was to give each group a title and illustrate its concept in a narrative and graphical way; this is to make the extracted data more workable when building the final framework.

3.3.2 Interviewees' background and experience

Interviewee No.1 is a research specialist who worked in an academic-industry research facility for many years. With a background in mechanical engineering, this interviewee has over twenty years experience in conventional cooling systems, thermal comfort, and issues of building energy use. He has been with a leading research program with a focus on RC systems for about six years. He is an active member of ASHRAE and has more than 50 published technical articles.

Interviewee No. 2 is an architect who has been practicing architecture for more than 20 years. Throughout his career he has won more than 65 major design and sustainability awards. He has designed two significant projects where RC systems were implemented. He is an adjunct faculty member teaching design courses in an American university.

Interviewee No. 3 is an architect with extensive experience in sustainable architecture and LEED design projects. He has won many design awards. As part of his approach to design, he pays attention to the materials used in his projects. The radiant system he designed was a custom system for a specific project. Through this custom design, he was able to best integrate the radiant system into this project, which achieved the LEED Platinum certificate.

Interviewee No. 4 is an architect with extensive experience in sustainable design for a wide range of building types. He is an active member of many professional committees focused on sustainability. His approach to sustainable architecture "considers both occupant comfort, control and health and the owner's long term asset value and return". He works within a design team with an integration approach to produce high performance solutions and energy conservation. He has five years of experience with radiant systems, and he has designed many projects with different radiant system types.

3.3.3 Interviews findings

3.3.3.1 Initial factors leading to RC systems being considered and preferred over conventional HVAC systems

All interviewees agreed that the energy efficiency of the radiant system and the higher quality thermal environment are the major factors in the decision to consider radiant systems over conventional HVAC systems.

All interviewees explained that energy efficiency was measured through different energy modeling software prior to the system implementation. Results revealed a large saving in the energy consumption when compared to an all-air system. This savings could reach 50% of the total energy used by conventional cooling and heating systems. Interviewee no.2 added that "with radiant systems, thermal comfort is directly delivered to the occupants and energy is not wasted on conditioning unoccupied spaces".

For the higher quality thermal environment, interviewee no.1 agreed with this point but he added that there is not enough research supporting this. He and the others explained that this benefit is due to the elimination of cool air movement inside the conditioned spaces, which is present in spaces with all-air systems. Interviewee no.2 added that having constant thermal conditions enhance the feeling of comfort for the occupants in these spaces.

Interviewee no. 4 added that another reason for using radiant systems is the ability to extend the natural ventilation mode in the building during the cooling season. He explained: “with RC systems the building could be naturally ventilated as long as the surface temperature of the system is higher than the dew point temperature. This could extend the natural ventilation mode and thus reduce energy use while having a better thermal environment and higher IAQ inside the space”.

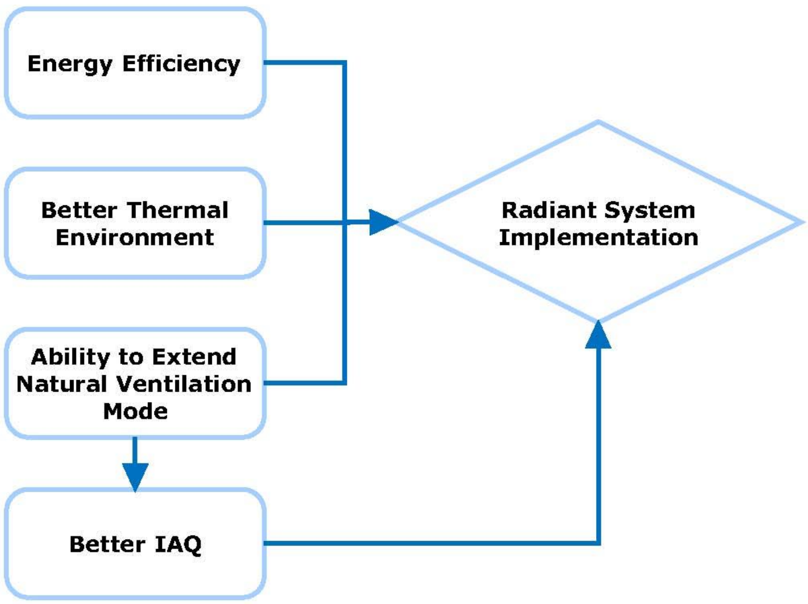


Figure 3.99. Initial factors leading to RC systems being considered and preferred over conventional HVAC systems as explained by the interviewees

3.3.3.2 RC system type

There are two common types of radiant systems mentioned by the interviewees; the slab system and the ceiling panel system. Interviewee no. 4 also had experience with capillary tubes covered with plaster (see section 1.2.3 for more details), which is similar to the ceiling panel system in its operation. The following points are the major differences between the two systems as mentioned by the interviewees:

Ceiling panels system

a) Radiant ceiling panels are easier to design than the slab system. Their cooling and heating capacity are pre-specified by manufactures. Other properties are pre-determined and measured by the manufacturer.
b) They are usually modular in their construction.
c) They have been used longer than slab systems; therefore some design guidelines are available for their design and implementation.
d) They are quicker to respond to changing heating/cooling loads when compared to the slab system.

Slab systems

a) The system is designed differently for each project depending on a wide range of variables such as space function, cooling/heating loads, solar heat gain, physical loads on the slab, slab on grade or multi-story slabs, etc.
b) The system has a long time-lag, therefore it responds more slowly to changing loads when compared to ceiling panel systems.
c) If the floor side is the thermally active side, floor covering should be minimized.

Interviewee no. 4 mentioned that the capillary system has almost the same criteria for design as the radiant ceiling panel system in terms of control and response time to changing loads.

Interviewee no. 1 said that there is no significant difference between the ceiling system and the slab system from the energy consumption point of view.

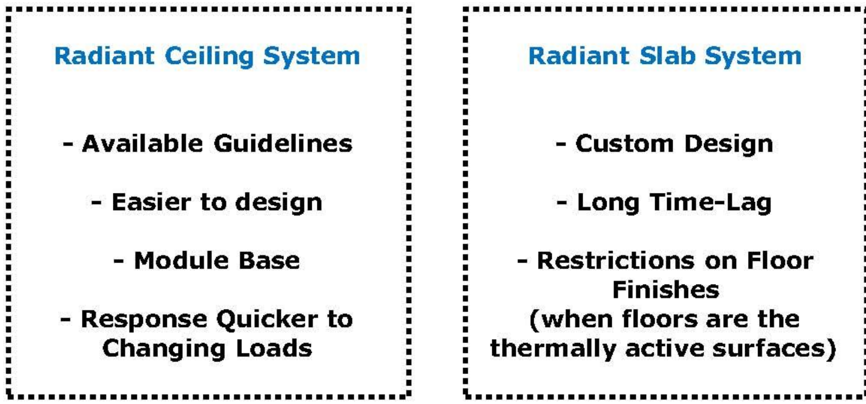


Figure 3.100. Difference between radiant ceiling systems and radiant slab systems as mentioned by the interviewees

3.3.3.3 Influence of the building type on the decision to use RC system

All interviewees indicated that the decision to use a radiant system is related specifically to the space function and the space geometry and could not be generalized according to the building type. In theory, radiant systems could be installed in any building type, but when it comes to the space level, each space has its requirements and priorities and integrated design thinking is the key for successful results.

Interviewee no. 1 explained that the metabolic rate of the occupants inside the space is a key factor. He explained that chilled slab systems would work better in spaces where occupants have a high metabolic rate such as shopping centers, whereas in spaces where people are seated radiant ceiling panels may provide a more thermally comfortable environment. He added, that if high metabolic rates would produce large latent cooling loads, questions should be asked about the system implementation's cost and energy saving potentials.

Interviewee no.4 indicated that the nature of the space function is another key design factor. In spaces where the heating and cooling loads do not fluctuate rapidly, slab systems work well. Whereas spaces which require quick response to dynamic cooling and heating loads, radiant ceiling panels systems and capillary tubes will work better due to their quick response time.

He also added that in the case of radiant slab systems, designing the slab with the ceiling side as the thermally active surface is preferable, as long as the ceiling is at a normal height. This is due to the fact that the ceiling has a bigger view angle value than the floor; this makes the radiant heat exchange more efficient for the ceiling side case. Also, floors could be covered by carpet and/or furniture and that will affect the radiant heat exchange between the active surfaces and the occupants.

Interviewees no. 2 and no. 3 said that radiant systems can be implemented in any space as long as its geometry and its function are well considered and studied. They mentioned that it is all about how much the designer is comfortable with the system, and the knowledge and experience he/she has.

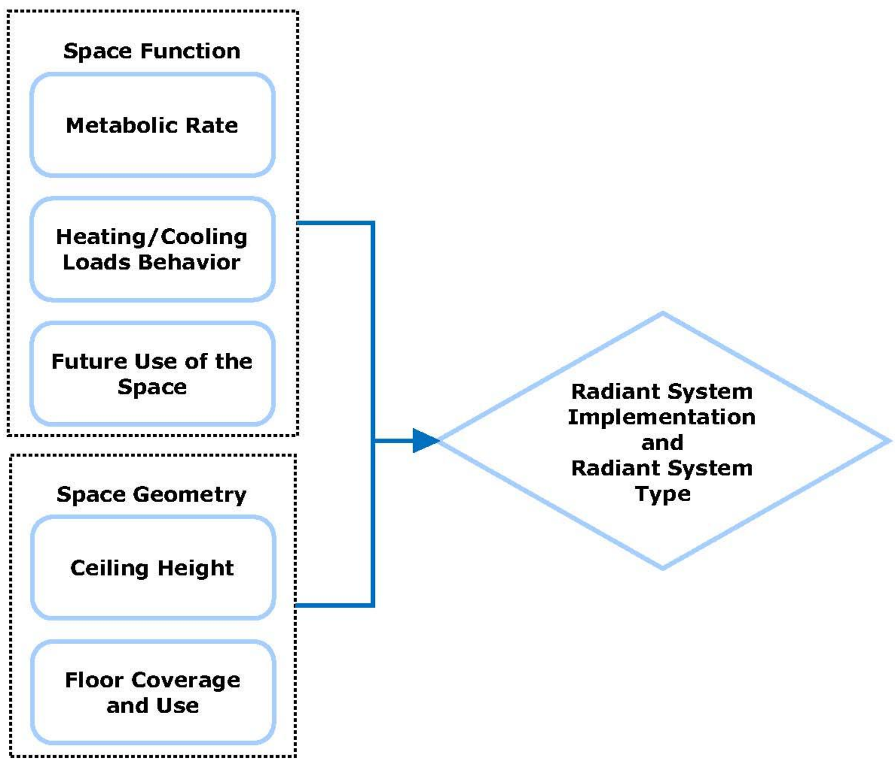


Figure 3.101. Influence of the space type over the decision to use RC system as mentioned by the interviewees

3.3.3.4 RC system and decision making process

There is an agreement between all interviewees that the first step in the system implementation process is to analyze and fully understand the following points:

a) Space function
b) Humidity behavior inside the space

c) Heating and cooling loads

d) Space geometry

Space function:

i. Space function is a major variable in calculating the internal cooling loads (sensible and latent), and based on these calculations the radiant system will be designed to have a certain cooling capacity value, and consequently another decision will be made concerning whether there is a need for a supplementary cooling system or not.

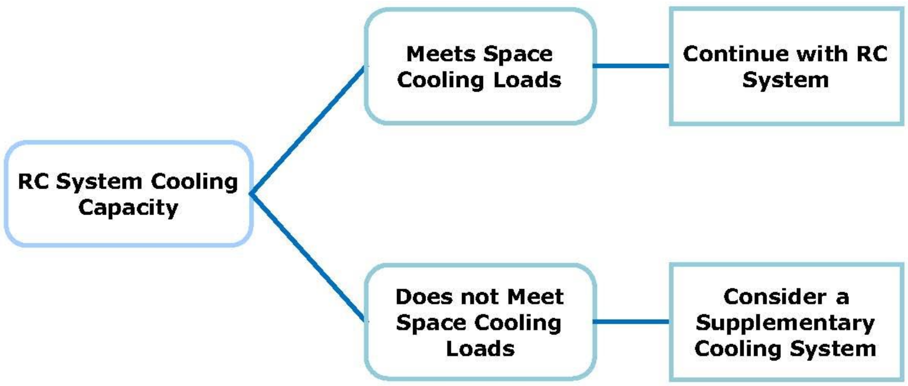


Figure 3.102. Space function variable in the decision making process as mentioned by the interviewees (decision tree)

ii. The space function will determine the nature of the cooling loads, whether it is steady or fluctuating. In spaces with steady cooling loads such as most office spaces and library, a chilled slab could be implemented and operated at certain surface temperatures. However, in spaces with fluctuating cooling loads such as classrooms and meeting halls, the ceiling panel system is recommended as it can respond quicker to these sudden changes.

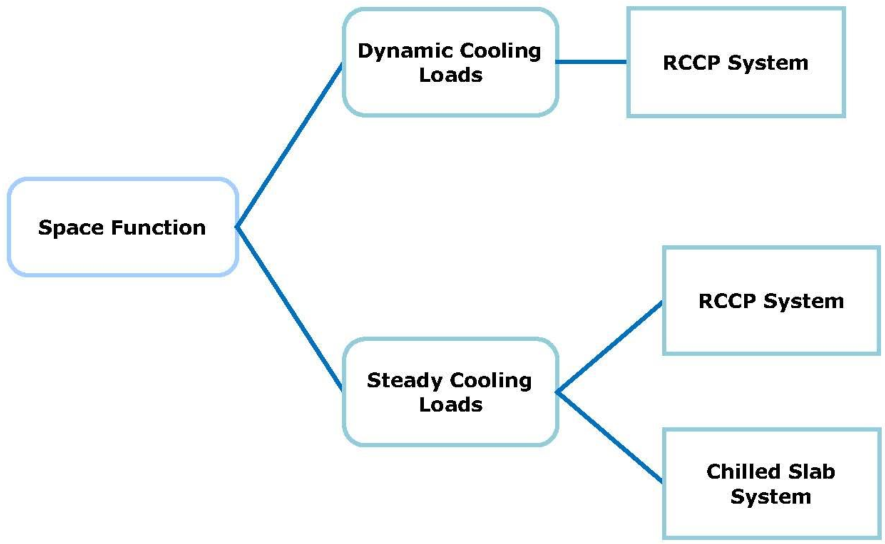


Figure 3.103. Space function variable in the decision making process of the system selection as mentioned by the interviewees (decision tree)

Humidity behavior inside the space

i. Radiant systems should be supplemented with a humidity control system when operating in the cooling mode.
ii. Interviewee no. 1 explained that if the humidity level inside the conditioned spaces is expected to be high and (above normal levels) and thus dehumidification is required, then the decision to implement RC system should be revised and reconsidered.

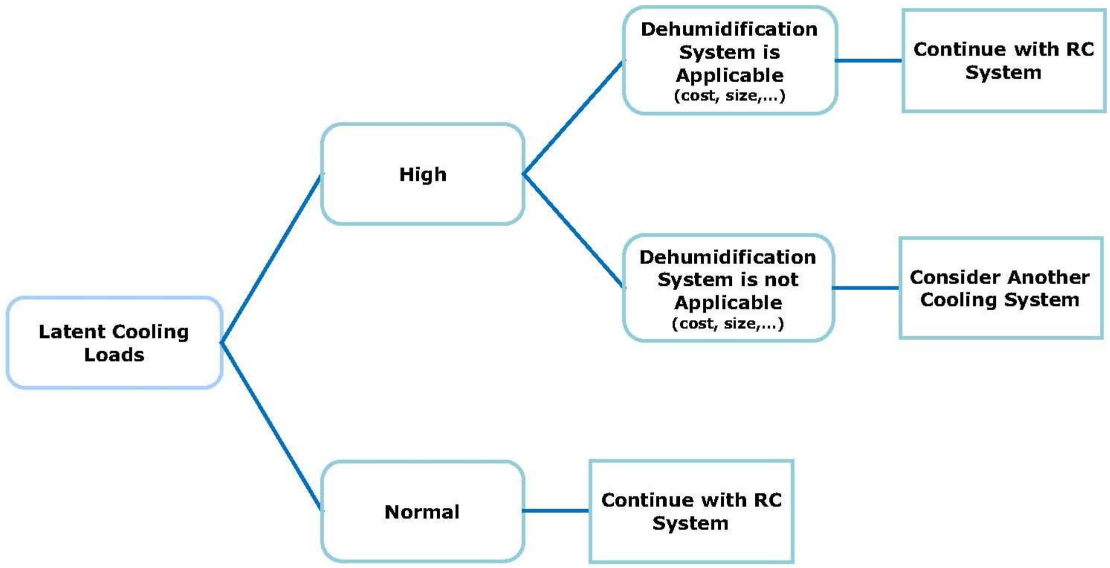


Figure 3.104. Implementing RC systems requires adapting a humidity control strategy as explained by the interviewees (decision tree)

Heating and cooling loads

All interviewees emphasized that before making the decision to implement a radiant system, the design team should set a goal to minimize the space cooling and heating loads. Minimizing the cooling and heating load could be achieved through different design steps and strategies.

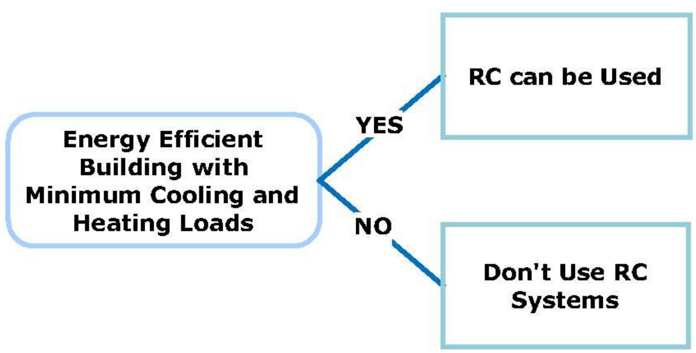


Figure 3.105. Implementing RC systems requires designing an energy efficient building as explained by the interviewees

Space geometry:

In high ceiling spaces, ceiling panel systems typically will not be effective and thus the radiant slab system will perform better.

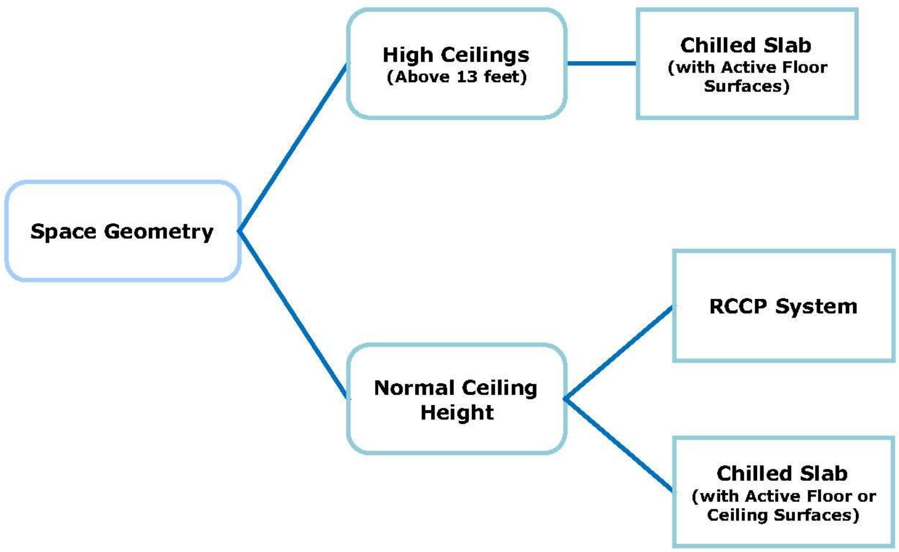


Figure 3.106. Space geometry variable influence the RC system type selection as explained by the interviewees (decision tree)

3.3.3.5 Endogenous variables

System cooling capacity

Interviewee no.1 mentioned that the cooling capacity of the RC system is directly related to the system surface temperature and limits such as dew point temperature in the conditioned space.

Interviewee no. 2 explained that this issue does not typically fall within the architect's domain, and the engineers should discuss this and inform the architect if the system will work and produce the desired thermal environment or not.

Interviewee no. 3 said that spaces with RC systems should be supplemented with air handling units to a) provide the need ventilation air, b) reduce the humidity level and thus enable the RC system to perform better, and c) provide cool dry air to help the RC system meet the space cooling loads when needed.

Interviewee no. 4 also mentioned the need for an additional cooling system in the space to support the RC system and meet the space cooling loads, as the RC system can satisfy the space sensible cooling loads most of the time but not typically all the time.

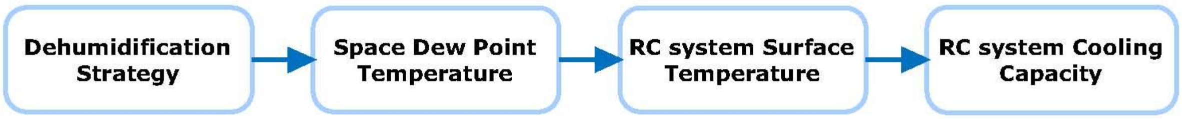


Figure 3.107. Sequential variables affecting RC system cooling capacity as explained by the interviewees

RC system surface temperature

Interviewee no.1 explained that the RC system surface temperature is related to the system cooling capacity and must be controlled by a Building Management System (BMS) to avoid possible failure or condensation. However, he added that condensation on the RC system surface will not happen instantaneously and will take time before the first drip occurs. He concluded by saying that there is not enough research explaining this point in detail.

Other interviewees said that this point is not a concern for the architect and it falls in the engineers' domain.

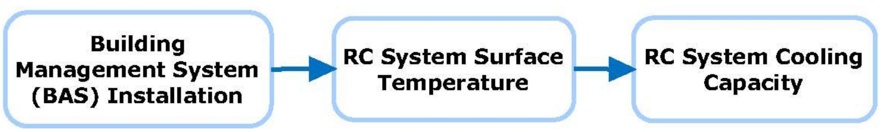


Figure 3.108. The influence of RC system surface temperature on the design process as explained by the interviewees

RC system control

Interviewee no. 1 explained that the RC system control is the key point when implementing the system. He explained that the control occurs through a) the ability to control the humidity level in the conditioned spaces with regards to the RC system surface temperature and comfort levels, b) the system surface temperature, and c) the ability to provide the needed cooling capacity as needed in the conditioned space.

All other interviewees agreed that the RC system should be automatically controlled by BAS, and this point is within the engineers' domain and are not the architect's concern.

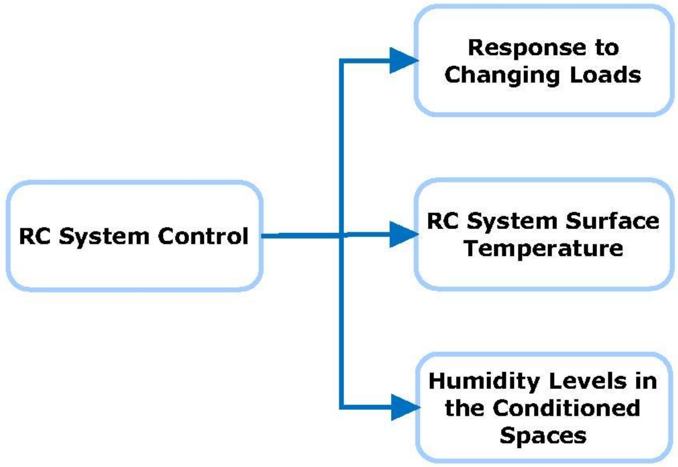


Figure 3.109. RC system control variable as explained by the interviewees

RC system physical properties

All interviewees agreed that the radiant system and the space function should be well understood and investigated while looking for potential integration possibilities with other systems in the conditioned space.

Interviewee no. 4 said that as the system will cover large areas of the space, it is the architect's responsibility to consider and think about the aesthetic appearance of the system.

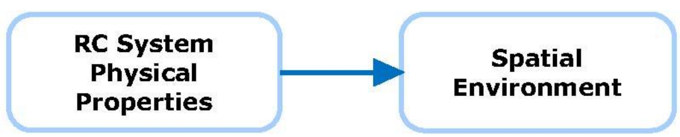


Figure 3.110. The physical properties of the RC system influence the spatial environment

3.3.3.6 Common barriers and constraints

One common constraint mentioned by all the interviewees was the lack of expertise and resources related to the design and implementation of RC systems in the U.S. Interviewee no. 2 added that this means that when you are buying the system you are buying some problems with it and the designer has to find the solutions. Interviewee no.1 explained that this point may make some designers hesitate to implement the system in larger buildings with multiple-thermal zones.

According to interviewee no.3, this point may make the design and implementation of a conventional HVAC system much cheaper due to the fact of having more competitors in the market than for RC systems.

Another common constraint is the space function and its future use with regards to the system opportunities and limitations as implementing radiant systems is not intuitive. The interviewees emphasize that the designer must understand the space function very carefully, including the adaptability of the space and the finishing materials. This point may present constraints especially on radiant slab systems. Interviewee no. 2 gave an example of having a chilled slab system, where the floors are the thermally active sides, and then having a function that required staged floor or the floor to be covered by carpet. Interviewee no. 3 added that in some spaces such as auditorium it would be very difficult to depend only on a traditional RC system to provide the desired thermal environment.

Interviewee no.4 added another constraint; that it is harder to convince the project owner to implement such systems because of bad experiences owners have had with the system in the past due to the misunderstanding of the system from design and operation points of view. Then he explained that this could be changed by developing new ways to overcome the previous failure points and by justifying the use of the system in the project such as the framework proposed from this research.

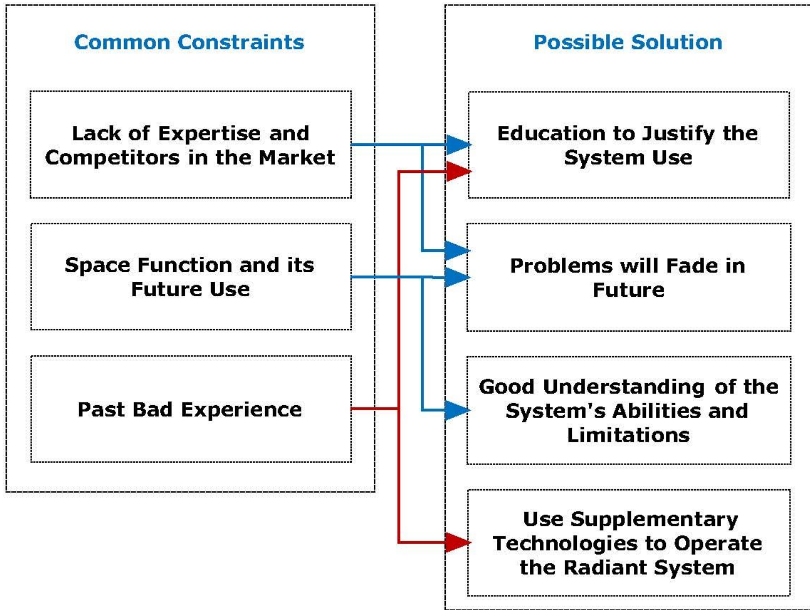


Figure 3.111. Common barriers and constraints mentioned by the interviewees and possible solutions

3.3.3.7 Design process

The design process of the RC system could be summarized in the following steps as the interviewees explained.

a) All interviewees agreed that the RC system design process should start by minimizing the space cooling loads, latent and sensible. Interviewee no. 3 explained that this step may include but not be limited to the following design strategies a) super insulation to minimize external conduction heat gain, b) solar shading to minimize solar heat gain c) daylight capturing to minimize the need for artificial light, d) having tight envelopes to minimize infiltration rate, e) designing the space to be big enough for its function, and f) minimizing the internal heat gain by using energy efficient systems.
b) Interviewee no. 3 described the next step as running energy simulation models using appropriate software to determine the building configuration that consumes the least amount of energy and results in the best thermal environment.
c) Start the cooling and heating load calculations to determine the radiant system configuration and its cooling/heating capacity. During this step, spaces with fluctuating loads should be considered and other systems should be decided upon.

d) The next step, according to interviewee no.1, is to decide on the control approach such as system time lag, dew point temperature limits, system surface temperature range, etc. This step, according to the other interviewees, is within the engineers' domain and the architect has little to do with it.

e) Interviewee no. 2 explained that the next step is to design the radiant system itself and start looking for integration possibilities. This has to be done with regard to the space function and its future use. He explained that this, in the case of radiant slab, may include but not be limited to the following points: pipe sizes, pipe location and spacing, how to protect the pipes during construction, vapor barrier location, and insulation layer. He emphasized that this step is not intuitive, especially in the case of radiant slab, and care must be taken.

f) Interviewee no.1 and interviewee no. 4 said that the last step would be to educate the occupants how to use this system as well as other systems in the building. This will help make the building systems perform as desired while providing a good environment.

Table 3.9. RC system design process as mentioned by the interviewees

Step	Design Process	Activity(s)
1.	Minimize the space cooling loads	Super insulation Daylighting Tight envelope Use energy efficient systems
2.	Run energy modeling simulation	To determine the best design configuration
3.	Heat and cooling loads calculations	Determine the radiant system cooling/heating capacity Determine the special spaces which may need supplementary systems
4.	Apply control systems	How to run the radiant system
5.	Design the radiant system	Looking for integration possibilities The final configuration of the radiant system
6.	Educated the occupants (Users)	To successfully run the system To improve the thermal comfort environment

3.3.3.8 Exogenous variables

Designer and client goals and preferences

All the interviewees mentioned that the client goals included building an energy efficient building. After acknowledging this goal, the design team started the evaluation of alternative cooling and heating systems. Computer energy modeling typically found that radiant systems have significant energy-saving potential. Interviewee no. 4 added that another reason for considering a radiant system was having a member of his design team with significant experience with radiant systems.

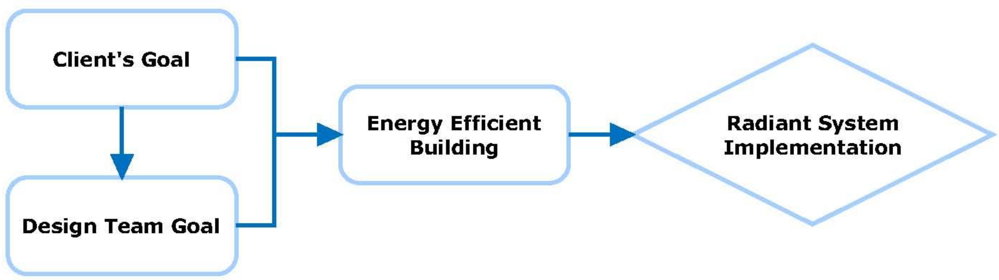


Figure 3.112. Client's goal and preferences in the decision making process as explained by the interviewees

Building codes and Standards

According to the interviewees, the American building codes and standards do not constrain the implementation of RC systems.

Climate (Outdoor environment)

All the interviewees indicated that the building envelope system has to be designed to protect the conditioned spaces from the outdoor environment factors, mainly solar heat gain and humidity intrusion. This protection is the initial step of the RC system implementation.

Interviewee no. 4 added that in hot humid climate zones additional air handling units are required to take care of the humidity if the indoor temperature reaches the dew-point. Also, these systems could help the RC system to meet the space cooling loads. He also recommended in hot humid climate zones to implement chilled slab and not ceiling panels. This is mainly because chilled slabs have a high level of forgiveness for condensation unlike ceiling panel systems.

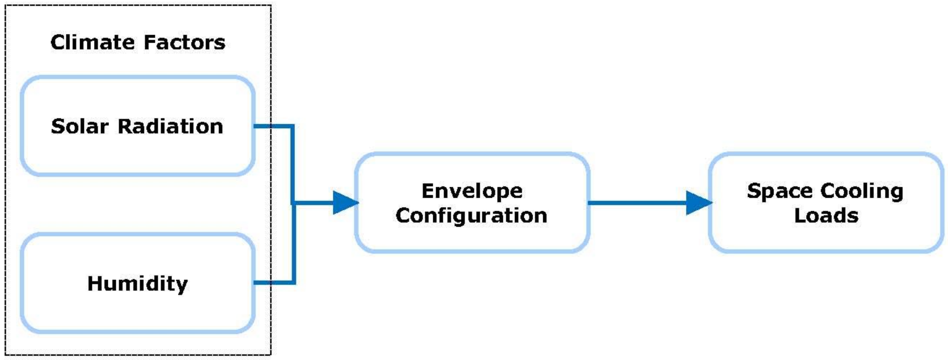


Figure 3.113. The influence of the climate factor on the RC system implementation as explained by the interviewees

Space function

All the interviewees emphasized that the space function is a major point in the decision making of the radiant systems implementation. Designers have to investigate three points for the space function: a) internal latent and sensible cooling loads, b) nature of the cooling loads, steady or fluctuating, and c) immediate and future use of the space.

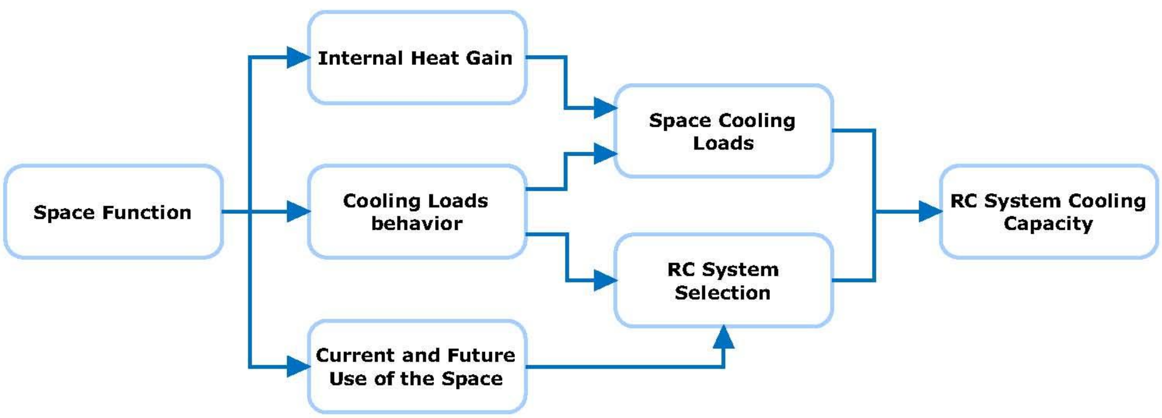


Figure 3.114. The influence of the space function on the RC system cooling capacity as explained by the interviewees

Space characteristics

Two major points under the space characteristics were mentioned by the interviewees:

a) Glazed area: all interviewees agreed that if the glazed area of the envelope system is designed to minimize the solar heat gain, then RC systems could be implemented and work successfully. Large untreated glazed areas in the building envelope will maximize the solar heat gain beyond the RC system cooling capacity.

Figure 3.115. The influence of the glazed area on the space cooling loads as explained by the interviewees

b) Ceiling height: for high ceiling spaces radiant ceiling panels typically do not work well, as the view factor value would decrease. The same applies for radiant slab systems if the ceiling sides are the primary thermal active surfaces.

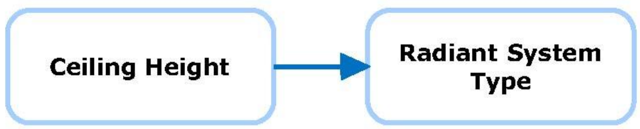


Figure 3.116. Ceiling heights affect the RC system type selection as explained by the interviewees

Additional systems in the space

Interviewee no.1 and interviewee no. 4 indicated that the system could be integrated in the space with any other system if the design team understands both systems. He also mentioned that the system could be easily integrated with the artificial lighting system.

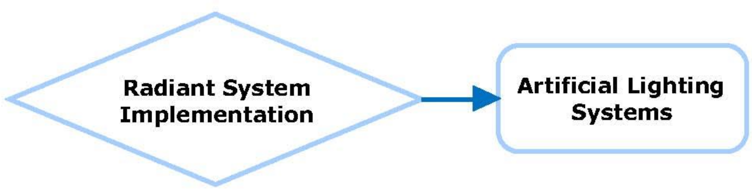


Figure 3.117. RC system implementation may affect the artificial light system design as explained by the interviewees

Ventilation strategy

Interviewee no. 2 stated that decisions related to the mechanical ventilation system selection are within the engineers' domain. He added that any mechanical ventilation system could work if it is designed properly. Other interviewees agreed that any mechanical ventilation system could work with the RC system.

Interviewee no. 4 indicated that natural ventilation is an option with RC systems if both are designed carefully. He added that one of the benefits of the RC system is to extend the natural ventilation mode period, which would reduce energy consumption and provide the desired thermal comfort environment.

Interviewee no. 3 added that the ventilation system is mainly to provide the for ventilation while maintaining a certain level of IAQ. However, this system may also be used to provide dry cool air to help the RC system meet the space cooling loads during extreme conditions.

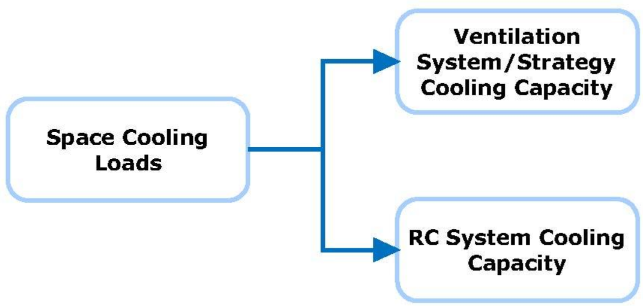


Figure 3.118. Ventilation strategy and the space cooling loads as explained by the interviewees

3.3.3.9 Thermal comfort

Interviewee no. 1 said that the key point to provide thermal comfort in spaces with RC systems is how the system is operated with regards to occupancy profile, heat gain and generation profile, response time, ventilation, and humidity level.

All interviewees agreed that the system would provide a better thermal environment when compared to conventional all-air systems. However, interviewees no.1 and no. 4 suggested that this is due to the fact that there is less cool air moving in the space and not because of the heat transfer mechanism between the occupants and the system itself. Having less cool air movement can limit the effects of draft.

Interviewee no. 2 said that the system would provide a constant operative temperature which may result in higher satisfaction with the thermal environment. Interviewee no. 4

indicated that having a more comfortable thermal environment was a driving force for using the system in his designs.

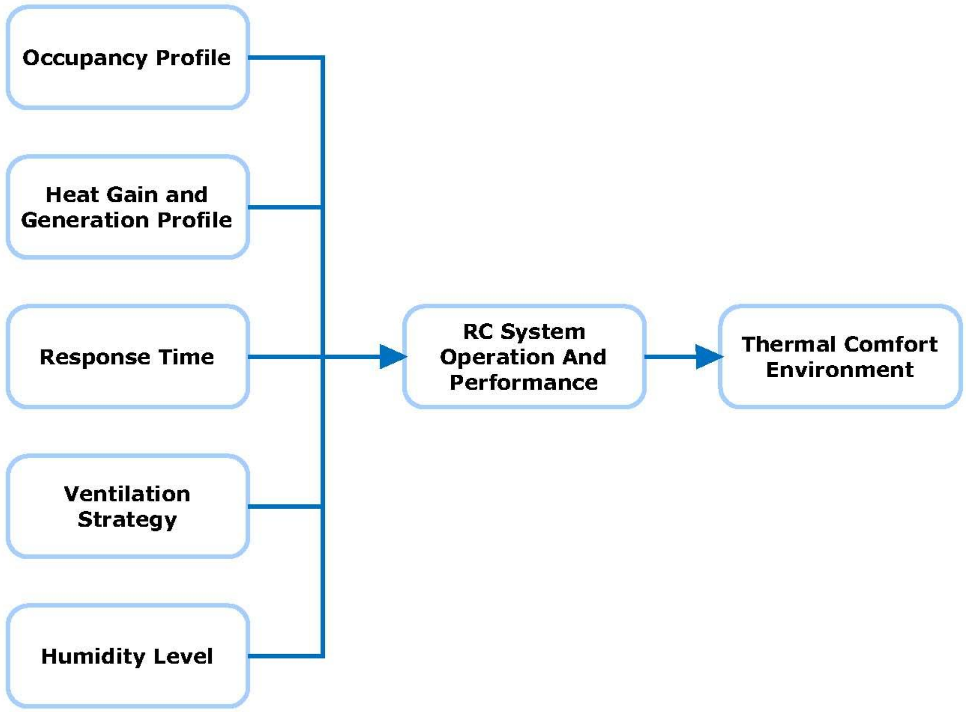


Figure 3.119. The effects of RC system implementation on the thermal environment as explained by the interviewees

3.3.3.10 IAQ

All interviewees indicated that the IAQ of the conditioned spaces could be improved when using RC systems when compared to using all-air cooling systems. They attributed referred this mainly to the fact of using DOAS and introducing 100% outdoor air to the space. However, none of the interviewees indicated that this was a main factor in the decision for RC system implementation. Interviewee no. 1 said that using a RC system would improve the IAQ but they are not directly connected, and not enough research supports this claim.

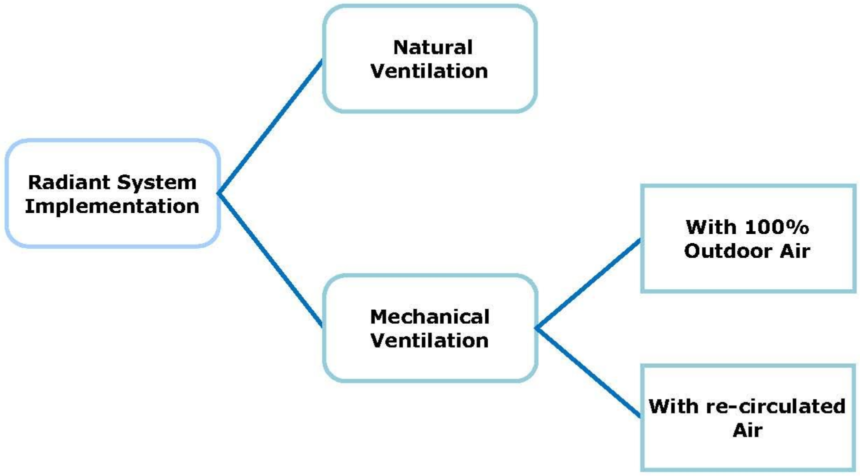


Figure 3.120. The RC system implementation may improve the IAQ environment as explained by the interviewees (decision tree)

3.3.3.11 Acoustics

Interviewee no. 2 stated that the acoustical environment should be assessed carefully in each space based on its function. This should happen in parallel with making the decision to implement the radiant system. He added that the advantages of having a silent system over often negated by the large hard surfaces the system needs for heat exchange.

Other interviewees think that the acoustical environment is a major concern but it is not a barrier for the implementation of radiant system. Solutions are available but they could be pricey and lengthen the radiant system payback time if the system is not designed carefully.

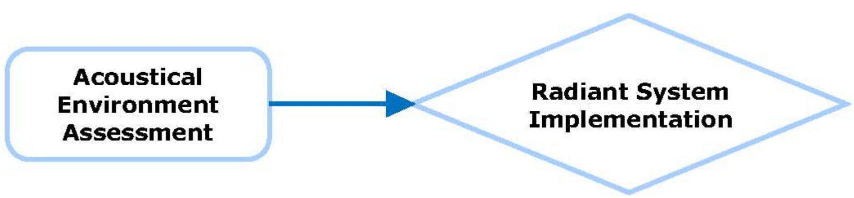


Figure 3.121. Acoustical environment assessment affects the decision of RC system implementation as explained by the interviewees

Interviewee no. 1 said that when dealing with the acoustical environment it is more critical for the radiant ceiling panel or radiant slab systems with active ceiling sides than for slab systems with active floor sides. Interviewee no. 3 added that careful design of the acoustical environment in the early stages of the design can prevent the problem before it happens.

Interviewee no. 3 said in general, in spaces where acoustics are not a big concern the implementation if the radiant system was not a problem. However, acoustical performance is still a big challenge in office buildings where privacy is required.

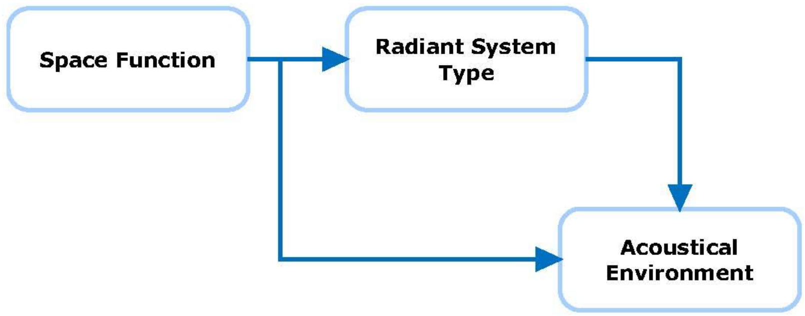


Figure 3.122. Space function and the RC system type influence the acoustical environment as explained by the interviewees

3.3.3.12 Visual

All interviewees said that the there are no limitations on window size and location when using radiant systems, as long as the glazed areas are designed to be efficient in terms of energy.

Interviewee no. 4 said that when implementing a radiant system, typically fewer and smaller ducts will be used, however, the thermally active surface will be more visible in the space. He added that, with the use of radiant systems, the potential to improve the space lighting environment is higher, but again that was not a factor in the decision for RC system implementation.

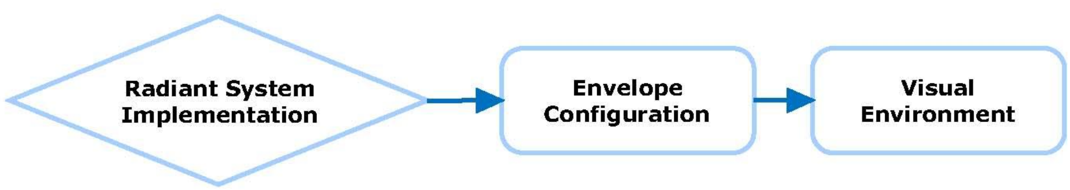


Figure 3.123. The implementation of a RC system may affect the space visual environment as explained by the interviewees

3.3.3.13 Recommendations

The interviewees had the following recommendations when considering a radiant system:

a) Think ahead and work within a team following the integration approach.
b) Understand the limitations and the capabilities of the system before using it.
c) Assess each space individually before making the decision to implement a radiant system. However, the system may not be used in all the project's spaces.
d) The more experience the designer has with the system the more he/she will find solutions for future implementations and avoids problems.
e) Education is a key point when implementing energy-efficient systems such as radiant systems.
f) Interviewee no. 2 added that the use of real-time power usage monitors will encourage the occupants to respond to their energy consumption and save energy.
g) Interviewee no. 2 explained that, when designing energy efficient buildings, while occupants' comfort is the main objective, designers have to think about the implementation of the lowest technology system available such as natural ventilation and radiant systems.
h) Interviewee no. 3 said that condensation and other possible constraints are all about how you design and integrate the radiant system in the space.
i) Interviewees no. 3 and no. 4 indicated that the high cost of the system is due to the lack of qualified competitors in the market and the unpopularity of the system in the American culture. They think the cost will drop dramatically if more competitors are in the market and when the system, like other cooling systems, is available off the shelf.
j) Interviewee no. 3 added that the system has to be justified to the owners and design team members like any other system in the building.

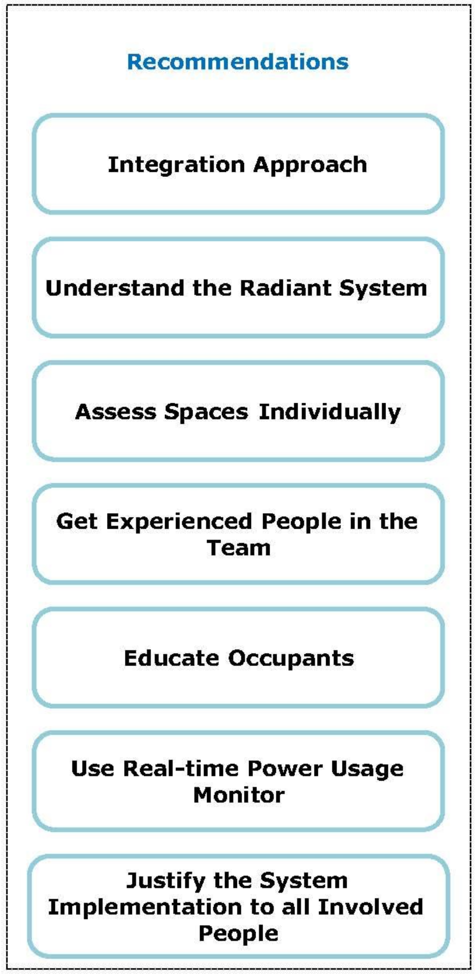


Figure 3.124. Recommendations for the RC system implementation as mentioned by the interviewees

4 DECISION-SUPPORT FRAMEWORK

4.1 Introduction

The decision-support framework for the design and application of RC systems is an analysis tool to be used mainly in the process of applying a RC system in a space or in a building. This framework, by identifying the relevant issues, barriers, constraints, and evaluation procedures relevant to the design and application of RC systems, will help architects and HVAC engineers exploring the architectural consequence of the systems' implementation in any given space.

Applying a RC system to a space or building will affect not only the thermal performance and IAQ of that space directly but will also influence compliance with the other building performance mandates indirectly. This application may also affect other issues such as the structural system, envelope configurations, etc. In this research, only issues related to building performance mandates will be discussed, namely: acoustical performance, visual performance, and spatial performance.

Explaining these relationships is to provide guidelines for the architect and the HVAC system designer when implementing RC systems. Also, the framework may yield some recommendations and/or provide notice when certain barriers or constraints are identified as serious obstacles to application for a given design scenario.

4.2 Framework Development Process

The development of the framework included the following tasks as indicated in the research methodology in section 2.6 and as shown in Figure 4.1:

a) Identifying the framework variables through the systematic literature review, the analysis of the case studies, and the interviews. These variables were identified as the ones which affect decisions and must be considered when implementing the RC system in the space under investigation.

b) Classifying the framework variables into different categories. This categorization is to build the framework's general structure. These categories are the framework inputs, the framework evaluative categories, and the framework assessment procedures.

c) For the framework inputs, the variables were classified into RC system endogenous and exogenous variables.

d) Adapting a set of relevant performance mandates from building codes, standards, and regulations as the framework evaluative categories.

e) Studying the relationships and interactions between the variables themselves, and between the variables and performance mandates, while establishing assessment procedures.

f) Mapping the framework variables. The framework was designed to be open for future development and easy to use by adopting a graphical language.

g) Acceptance of the framework.

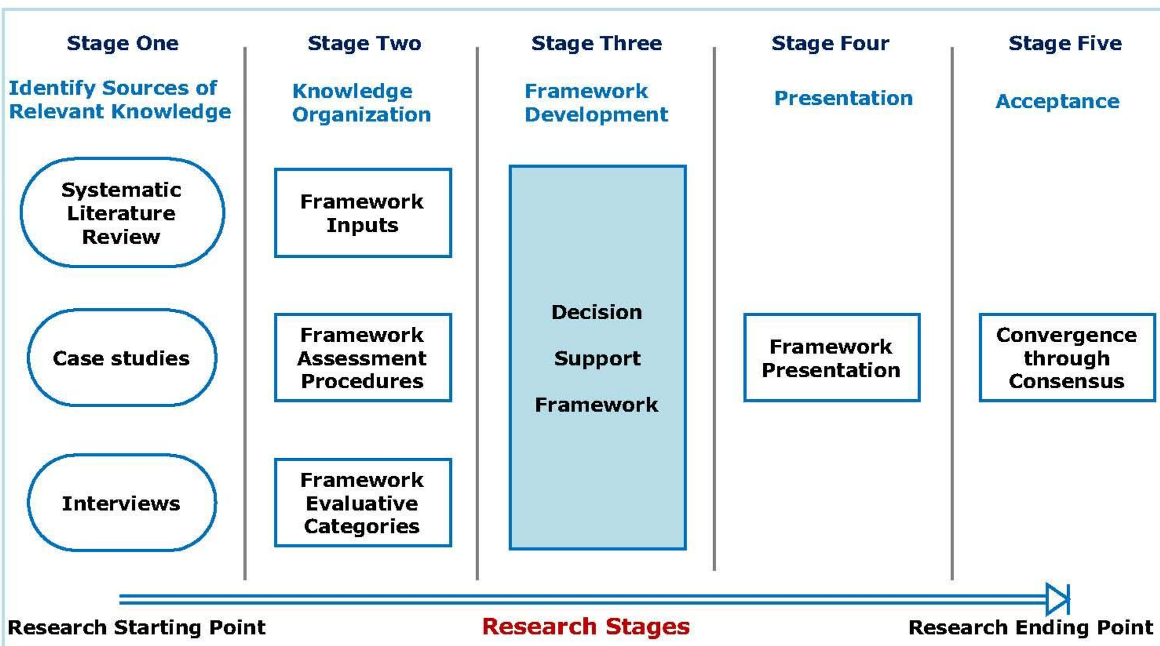


Figure 4.1. Framework development process

4.2.1 Framework variables

Many influential variables emerged from the systematic literature review, case studies analysis, and the interviews. Some of these variables tangibly affect the decisions related to the design and implementation of RC systems while the influence of others are less tangible. From this a set of variables was identified as those which may be used to evaluate the system implementation in light of the building performance mandates. The following sections identify, classify, and map these variables.

4.2.2 Framework inputs

The framework inputs are the variables which affect, directly or indirectly, the decisions related to the RC system design and implementation. These variables are divided into two groups; the first group is the endogenous variables and the second group includes the exogenous variables.

4.2.2.1 Endogenous variables (EnV)

Endogenous variables could be defined as the variables which are proceeding from within the RC system. They are derived from within the RC system, and their values are defined by the RC system characteristics. These values can be altered by the framework user, or they could be independent and fixed. RC systems endogenous variables include: the cooling capacity (EnV1), the surface temperature (EnV2), the control approach (EnV3), and the physical properties of the system (EnV4), as shown in Figure 4.2.

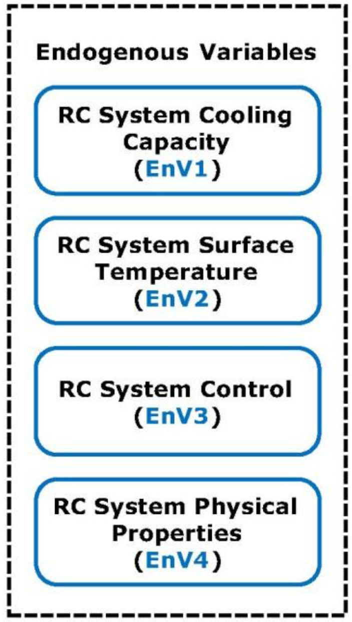


Figure 4.2. Framework endogenous variables

4.2.2.2 Exogenous variables (ExV)

Exogenous variables could be defined as the variables which are originating from outside the RC system. These variables could be dependent and can be altered by the framework user, or they could be independent and fixed such as the climate (outdoor environment). The values of these variables typically have direct and indirect effects on the configuration and performance of the RC system. Exogenous variables include: designer's and client's goals and preferences (ExV1), building codes and standards (ExV2), climate (outdoor environment) (ExV3), space function (ExV4), space characteristics (ExV5), construction system type (ExV6), and the ventilation strategy (ExV7), as shown in Figure 4.3.

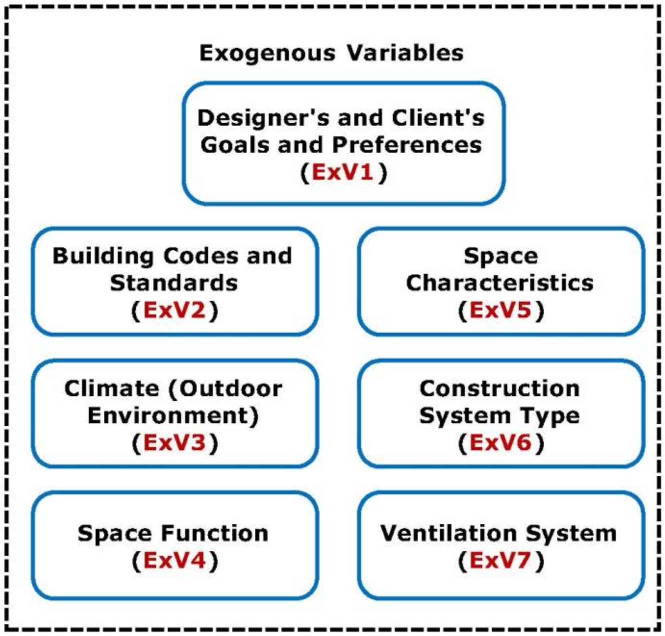


Figure 4.3. Framework exogenous variables hierarchy

4.2.3 Framework evaluative categories (EvC)

The framework evaluative categories are the expected performance of the RC system according to selected criteria. The building performance mandates are categorized into two groups: those which are directly related to the cooling systems, namely, thermal performance (EvC1) and IAQ (EvC2), and those which are not directly related to the cooling systems such as acoustical performance (EvC3), visual performance (EcV4), and spatial performance (EvC5).

The reason for this categorization is that RC systems are alternatives to conventional air-based HVAC systems. Typically, conventional HVAC systems are responsible for satisfying thermal comfort and IAQ. For this, the RC system performance is explained in detail in light of these two mandates. The framework evaluative categories are shown in Figure 4.4.

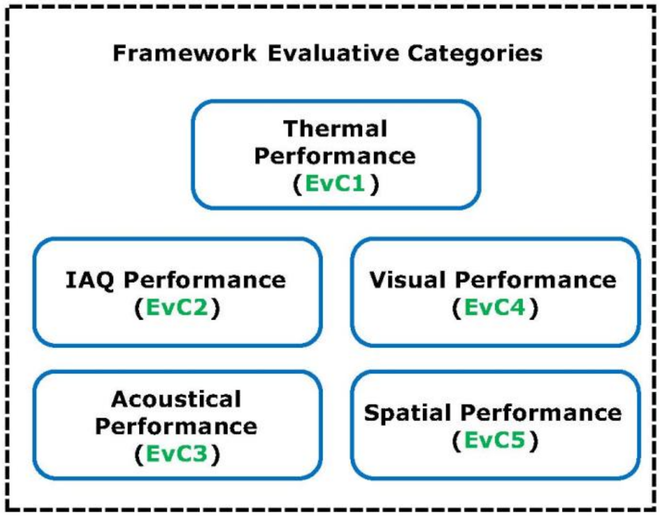


Figure 4.4. Framework evaluative categories

4.2.4 Assessment procedures

Assessment procedures are systematic methods of analysis which link the inputs to the evaluative categories. Assessment procedures are based on the systematic literature review, the analysis of the case studies, and the interview findings.

4.3 Framework Structure

Figure 4.5 shows the general layout of the framework structure:

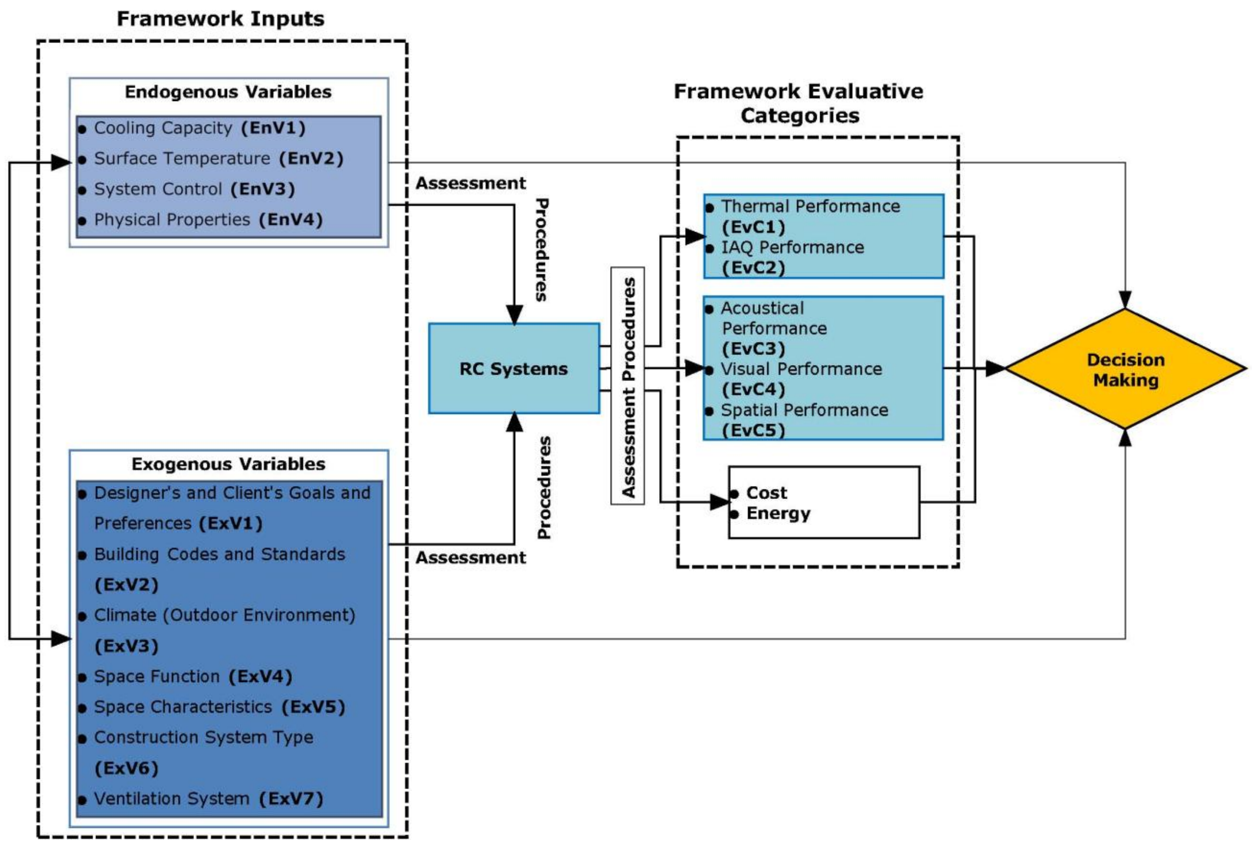


Figure 4.5. Overview diagram of the decision-support framework

Figure 4.5 shows an overview diagram of the decision-support framework. The framework inputs are classified into two groups; endogenous variables (light blue box) and exogenous variables (dark blue box). The interactions between these variables are explored. Then the effect of these variables on the design and application of the RC system is explained based on the assessment procedures found from the sources of relevant knowledge. After that, the effects of these variables on the relevant performance mandates are elaborated. It was noticed that some decisions relevant to RC system variables affect the final decision and those situations are explained.

In general, RC system implementation will affect the thermal and the IAQ environments of the space. It also influences, directly or indirectly, compliance with the other building performance mandates. By explaining and exploring these relationships, a guideline will be provided to the architects and HVAC engineers when considering RC systems. The framework also yields some recommendations and/or provides notice when certain barriers or constraints are identified as serious obstacles to application for a given design scenario.

4.4 Graphical Representation

The decision-support framework for the use and implementation of RC systems will serve a potentially broad set of users: architects, HVAC engineers, owners, building managers, etc., therefore it is important to use a language accessible to all users. A graphical language could serve this purpose.

As the framework is a decision-support tool which models different scenarios of decisions and their consequences, a graphical language such as a 'decision tree' could support this purpose and help visually illustrate the framework. The similarities in the characteristics of applying an analytical decision-support tool and the implementation of a RC system such as complexity, uncertainty, and multiple and competing objectives, makes the use of the graphical language of a decision tree an appropriate tool. A decision tree can encapsulate big problems into simple diagrams and can explain the consequences of each alternative.

A decision tree is a visual and analytical decision support tool, where the expected values (or expected utility) of competing alternatives are calculated. Olivas (2007) described decision trees as "a graphic approach to compare competing alternatives and assign values to those alternatives by combining uncertainties, costs, and payoffs into specific numerical values." He also mentioned the advantages the decision tree offers over other methods of analyzing alternatives, which are:

a) *The ability to represent decision alternatives, possible outcomes, and chance events schematically (graphically).*

b) *Efficiency by quick and clear expression of complex alternatives.*

c) *Revealing, the ability to compare competing alternatives, even without complete information, in terms of risk and probable value.*

d) *Complementary; the ability to use decision trees in conjunction with other project management tools. For example, the decision tree method can help evaluate project schedules.(p.3)*

The rules for decision trees are introduced as the following: decision nodes are commonly represented by squares, chance nodes are represented by circles, and end nodes are represented by triangles. For each decision node there are splitting paths – they do not meet later- which represent sets of decision alternatives that are available, where only one alternative can be selected. The end nodes represent the final outcome of a decision path. Figure 4.6 shows an example of a decision tree for a financial institution to decide whether a person should be offered a loan.

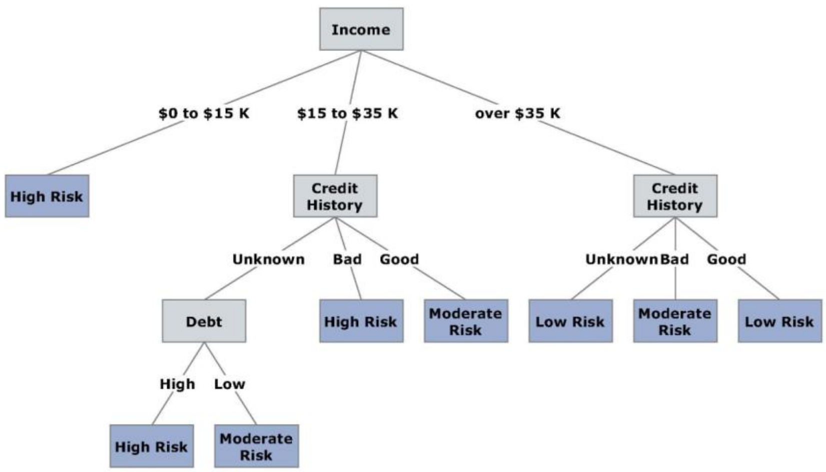


Figure 4.6. An example of a decision tree for a financial institution to decide whether a person should be offered a loan
Source: SmartDraw templates library, 2009

To represent the framework variables' relationships, influence diagrams could be useful. Influence diagrams are compact versions of a decision tree and contain elements with assigned meaning. Clemen explains these elements in his book: *Making Hard Decisions* (1996): rectangles represent decisions, circles or ellipses represent chance events, and rounded rectangles represent consequences, calculations, or constant values. In addition, arrows are used for connecting a predecessor node to a successor node and are called arcs.

Clemen (1996) added that arcs are referred to as relevance arcs when they are pointing into a chance node, or when they point to a consequence, calculation, or constant node. Relevance arcs are any predecessor nodes pointing to these nodes and that have an impact on the outcome of their successor nodes. He explained also that sequence arcs point to a decision node, which causes the decision-maker to take the benefit of the information represented by any predecessor node connected to that particular successor decision node before making the decision. These relations are presented graphically in Figure 4.7:

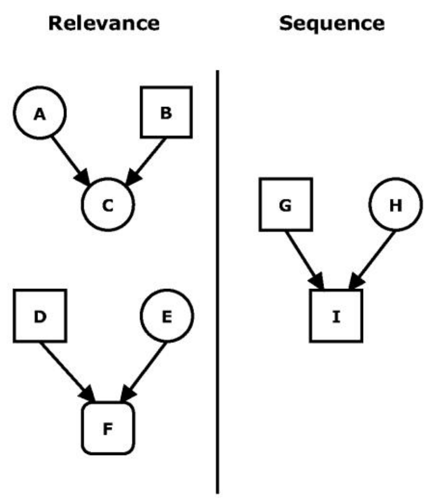


Figure 4.7. Graphical rules of influence diagrams
Source: (Clemen 1996)

Some additions have been added to the influence diagram language to better serve this research and make it easier to read as shown in Figure 4.8.

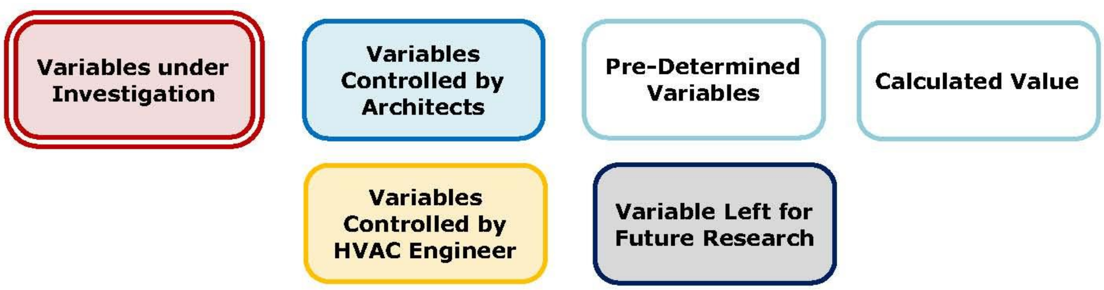


Figure 4.8. Additions to the influence diagram language

These additions include:

a) Variables under investigation are presented in double-red-line-rounded rectangles with light-red background. This is to help the framework user to distinguish easily the variable under investigation.

b) Variables controlled by architects are presented in blue rounded rectangles with light-blue background.

c) Variables with pre-determined values such as climate, space function, etc. are presented in light-blue rounded rectangles.

d) Variables which will be left for future research are presented in black rounded rectangles with gray background.

Also, the influence diagram is divided vertically into three categories to make it easier to read and follow. The first category is the ‘boundary conditions’ which contains mainly the pre-determined variables, the variables in this category cannot be changed or altered by the decision maker. The second category is the ‘decisions’ which contains the variables the decision maker have to decide upon, these decisions are made by the architect or the engineer. The third category is ‘outcomes’ which contains the variables that will be affected previous decisions, this category contains mainly ‘calculated value’ variables.

Based on the influence diagram language presented previously and the CBA language, a complete structure of the decision- support framework using an influence diagram approach is shown in Figure 4.9:

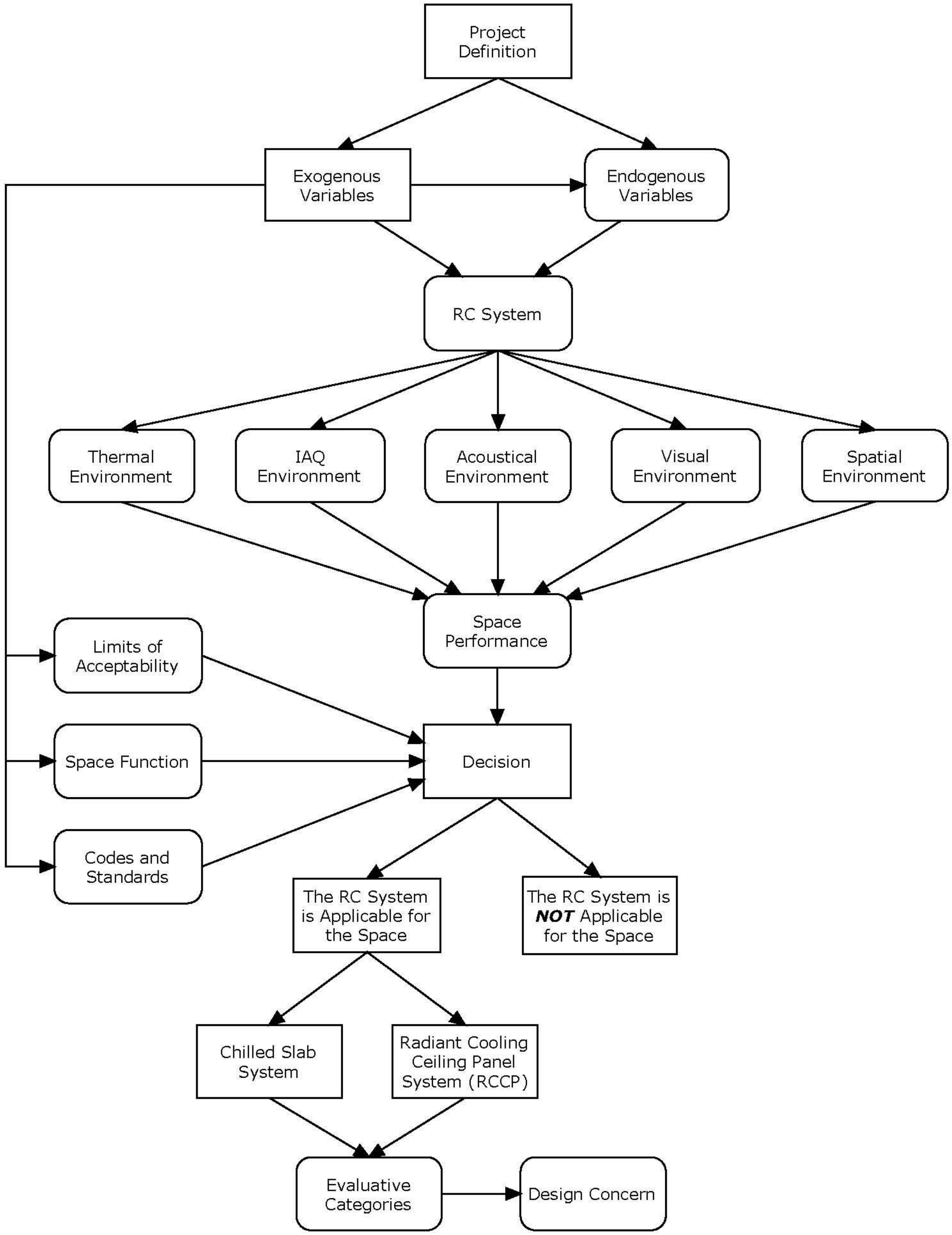


Figure 4.9. Influence diagram of the proposed framework

4.5 Mapping the Variables

In this section the framework endogenous variables and exogenous variables will be mapped to show all possible relations and to explain their affect on the decision of implementing a RC system. These maps, using the influence diagram language, will help the framework user in the implementation assessment process to see whether the RC system is applicable or not for the space under investigation and to understand the consequences of this implementation from an architectural perspective.

4.5.1 RC system cooling capacity (EnV1)

As explained in sections 3.1.1.1.1, 3.2.7.1, and 3.3.3.5 there are many variables which could affect the cooling capacity of the RC system. It should be noticed that not all of these variables have the same influence on the RC system cooling capacity. These variables are mapped as shown Figure 4.10. The architect through design decisions can alter the RC system cooling capacity. These variables are highlighted in light blue. Also, the HVAC engineer's decisions for some variables, highlighted orange, will affect the RC system capacity.

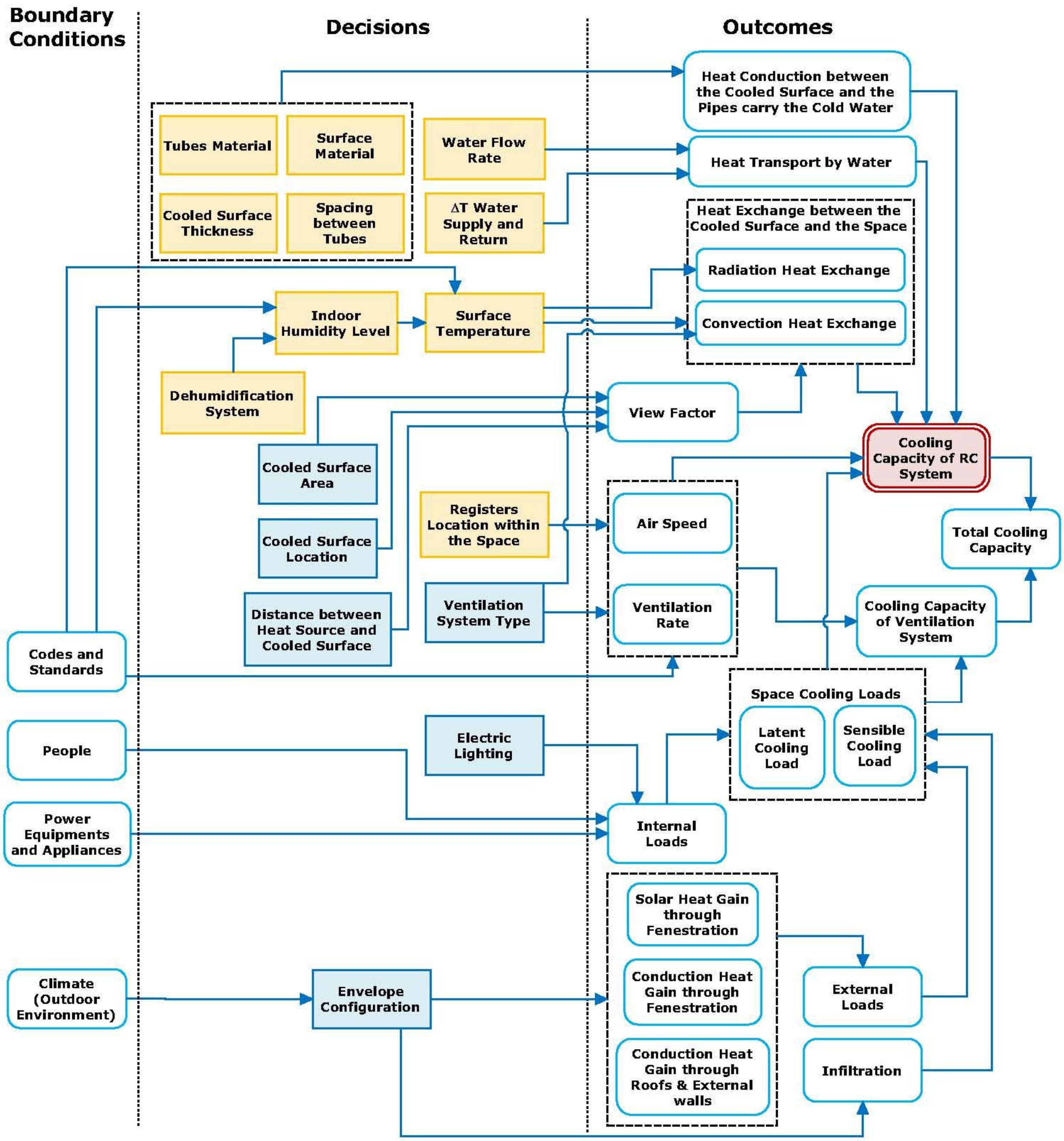


Figure 4.10. Influence diagram for the RC cooling capacity variable (EnV1)

Discussion:

The calculated variables affecting the RC system cooling capacity can be grouped as follows:

a) The RC system configuration; they include the heat conduction between the cooled surface and the pipes that carry the cold water, heat transport by water, and heat exchange between the cooled surface and the space (**EnV1a**).
b) The supplementary ventilation system in the space (**EnV1b**).
c) The space cooling loads (**EnV1c**).

(EnV1a)

i. For the heat conduction between the cooled surface and the pipes, there are four variables affecting this value; the tube material, the thermal characteristics of the material covering/attached to the pipes, the thickness of the cooled surface, and spacing between the pipes. Although all of these variables are typically controlled by engineers, the architect's decision of selecting the material the pipes are embedded in and choosing the thickness of the cooled surface can alter the heat conduction value.

ii. For the heat transport by the water, there are two variables affecting this value; the water flow rate and the ΔT of the supply and return water. Both of these variables are decided upon by the engineer.

iii. For the heat exchange between the cooled surface and the space, this value is affected by the following variables; a) the surface temperature of the cooled RC system, b) the view factor between the cooled surface and the space, and c) the ventilation system type.

   a) The surface temperature of the RC system (see the discussion of EnV2).
   b) The view factor value depends on the cooled surface area and its location relative to the position of the occupant. In general, the value of the view factor for the RCCP system or slab system with active ceiling side is higher than for the chilled slab system. The view factor value decreases when the ceiling height increases. Also, the larger the area of the cooled surfaces the higher the value of the view factor. Sections 3.1.2.3.6 and 3.1.2.3.7 discuss the view factor in detail.
   c) The ventilation system type; When using a mechanical ventilation system, the RCCP cooling capacity would increase from 5% to 35% when compared to

non-mechanical air movement (Jeong and Mumma 2004). See the discussion of (ExV7)

(EnV1b)

The supplementary ventilation system type will affect the RC system cooling capacity as discussed in (ExV7).

(EnV1c)

RC system can satisfy the space sensible cooling loads most of the time but not typically all the time. An additional cooling system is needed to support the RC system and meet the space cooling loads. If the space cooling loads are high, then the designer needs to increase the RC system cooling capacity. The space cooling loads is the summation of a) the internal heat load gains, b) external heat loads gain, and c) the infiltration.

i. The internal heat loads are affected by occupants' number and metabolic rate, the heat generated by the power equipments and appliances, and the heat generated by the artificial lighting systems inside the space. The architect's decisions related to the lighting strategy would affect this internal heat gain value.
ii. The external heat load gains are affected by the solar heat gain through fenestration, conduction heat gain through fenestration, and conduction heat gain through roofs and external walls. All of these can be determined by the architect's decisions for the building envelope configuration design with respect to the surrounding environment. The envelope configuration and the climate variables are discussed in detail in (ExV5) and (ExV3) respectively.
iii. The infiltration rate, which is an important variable in the calculation of the latent loads, is affected by the envelope configuration design and outdoor environment conditions.

Points to consider:

a) Jeong and Mumma (2004) mentioned, based on a study done by Kochendorfer in 1996, that the cooling capacity of the ceiling system is about 25% higher in real buildings as compared to what is measured in a laboratory. This is due to testing standards applied in the labs.

b) When implementing a chilled slab system, the slab (floor and/or ceiling side) will absorb heat throughout the day (operating hours), and therefore the cooling may be provided more uniformly. Also, during the non-operating hours the slab could be recharged for use the next day, which could minimize the size of the building cooling plant (Moe 2010).

c) The use of RC systems must be in combination with other strategies to minimize the space cooling load and to best utilize the ventilation system. (Moe 2010; Olesen 2002; Simmonds et al. 2006; Jeong and Mumma 2003).

Conclusion:

The architectural decisions that may influence the RC system cooling capacity are:

a) The cooled surface area, its location, and its surface temperature.
b) The selection of the RC system type.
c) The use of a mechanical ventilation system in the conditioned space.
d) The envelope configuration with regard to the surrounding climate.

4.5.2 RC system surface temperature (EnV2)

As discussed in sections 3.1.1.1.2, 3.2.7.2, and 3.3.3.5, the surface temperature of the RC system plays an important role in determining the cooling capacity and in providing thermal comfort while avoiding radiant temperature asymmetry. Figure 4.11 maps the RC surface temperature variable.

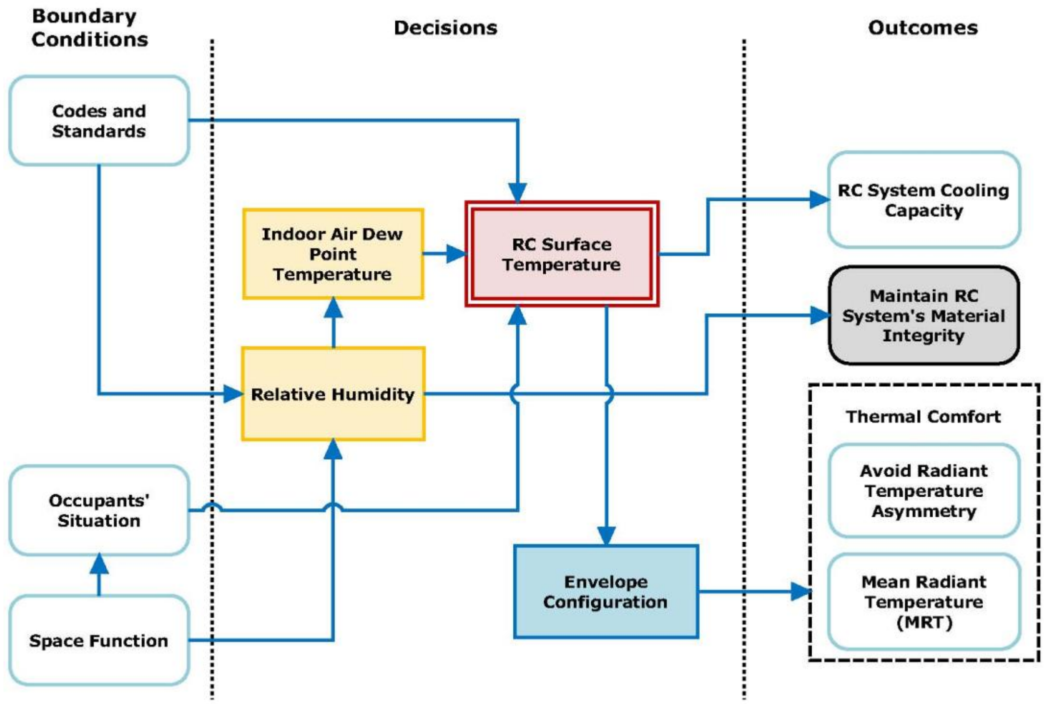


Figure 4.11. Influence diagram of the RC surface temperature (EnV2)

Discussion:

a) The RC system surface temperature is a major variable in determining the system cooling capacity.

b) The building envelope should be designed carefully to avoid creating relatively hot surfaces. This will maintain the operative temperature within its limits as defined by ANSI/ASHRAE 55-2004 as discussed in section 3.1.2.3.4. Also, this will avoid the creation of radiant temperature asymmetry situations which are limited by ANSI/ASHRAE 55-2004 standards as explained in section 3.1.2.4.1.

c) If occupants are in direct contact with the RC system cooled surface, as in the case of a chilled slab, standards such as ANSI/ASHRAE 55-2004 set a range of recommended temperatures as discussed in section 3.1.2.4.4. However, these temperatures are also governed by the indoor dew point temperature to avoid condensation on the cold surfaces. The situation of the occupants, be it standing or seated and clo value also affect the system surface temperature.

d) It is important to keep the RC system above the indoor dew point temperature all the time to avoid condensation, even if dripping will take time to occur, to maintain the material integriety of the system and to avoid IAQ problems.

Conclusion:

Designing the RC system surface temperature is typically within the engineers' domain. The architectural design decisions are important to avoid radiant asymmetry situations and the creation of condensation on the cooled surfaces.

4.5.3 RC system control (EnV3)

As discussed in sections 3.1.1.1.3, 3.3.3.5, and 3.2.7.4, there are at least five variables to be controlled when implementing RC systems in a space; the RC system cooling capacity, the RC system surface temperature, the indoor RH, the space operative temperature, and zoning the systems accordingly. These points are mapped as in Figure 4.12.

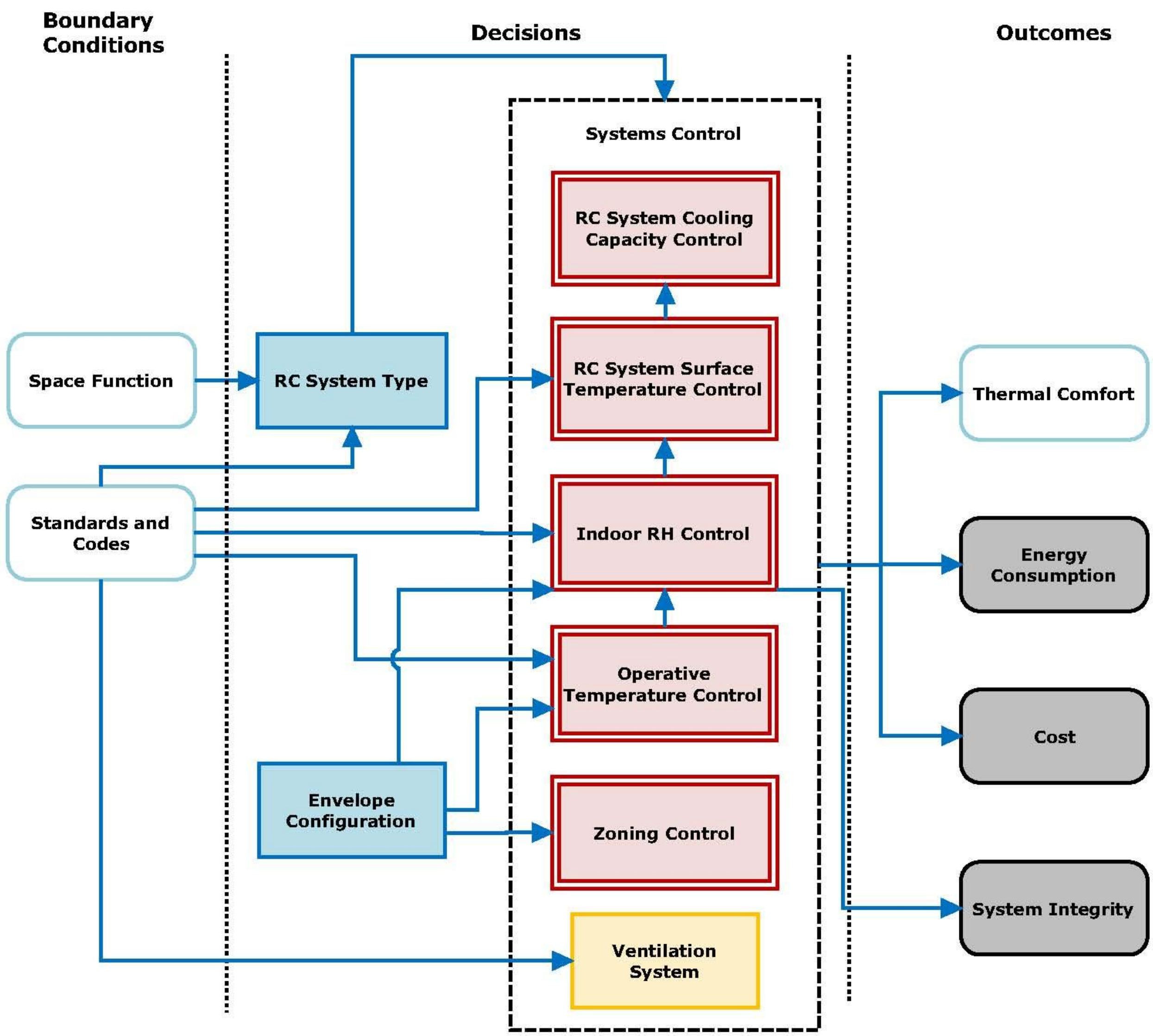


Figure 4.12. Influence diagram of the RC system control variable (EnV3)

Discussion:

As revealed from the case studies analysis and the interviews, the Building Management System (BMS) will control all five of the variables mentioned previously. These variables are governed, generally by the standards and codes and the space function. The architect selection of the appropriate RC system type and the envelope parameters define the control variables and their ranges.

a) Based on the space function, the RC system should be selected accordingly. See the discussion of (ExV4).

b) The system surface temperature affects the RC system cooling capacity. Also this variable is governed by standards and codes, and the space function. See the discussion of (EnV2). Time lag is another important issue when selecting the RC system. Chilled slab systems, due to their high thermal inertia, are slow to react to rapid cooling load changes, and it may take time for the surface to reach the desired temperature. On the other hand, RCCP systems respond quicker and the surface temperature could be changed much quicker with less mass. However, this condition should be considered carefully with respect to the space function which is a major factor in determining the nature of the space cooling load as being steady or dynamic.

c) One of the potential constraints when implementing RC systems is the indoor relative humidity as water vapor may condense on the cooled surface. Having control over this variable is important to sustain functionality of the system. RH values are related to acceptable indoor operative temperatures as defined by codes and standards, see section 3.1.2.3.9. When implementing a RC system, condensation prevention strategies are required, and it may be achieved by adopting at least one of the following strategies:

    i. Keeping the cooled surfaces' temperature at all times above the indoor dew point temperature by at least 3.6 °F (2 °C) (Feustel and Stetiu 1995). This has to be done with respect to the RC system cooling capacity, codes and standards like ASHRAE 62.1.

    ii. Humidity prevention can be maintained through controlling envelope air leakage. When "complying with ASHRAE Standard 90.1-1999, section 5.2.3, envelope air leakage would not be a problem" (Mumma 2001).[1]

    iii. Designing the space/building to be under positive pressure relative to the ambient would help control moisture intrusion (Byron Wender, personal communication, April 8, 2009).

    iv. Introducing cool and dry air to the space to satisfy latent cooling loads in the space (Jeong and Mumma 2006).

[1] In ANSI/ASHRAE Standard 90.1-2007 section 5.4.3 deals with Air Leakage.

d) Controlling the space operative temperature is important to achieve the desired level of thermal comfort and to avoid unacceptable asymmetrical thermal radiation or any other thermal discomfort situations. This could be achieved by:

   i. Controlling the RC system surface temperature with respect to the other relatively hot surfaces such as windows, and as described in ANSI/ASHRAE 55- 2004 and as shown in Table 3.3.

   ii. Carefully considering the location and the area of cooled surfaces to avoid asymmetrical thermal radiation.

e) Zoning:

   i. Having different zones within the same space may be important for occupant thermal comfort control. Multiple zones may accommodate different cooling loads that may occur within the same space such as locations near hot surfaces, while giving the occupants the ability to control their own space conditions (de Dear and Brager 1998).

   ii. In general, buildings have different thermal zones with different cooling loads. RC systems should have the flexibility to accommodate such variety. This will affect the initial installation cost of the system as well as the energy consumption of the system.

Conclusion:

When implementing a RC system in a given space, there are at least five points of continuous monitoring to maintain a successful operation of the system. A BMS is normally used in such a situation. The architectural decisions, of the RC system selection and the envelope configuration, will determine the values and ranges of these controlled points, with regards to the space function and the relevant codes and standards.

Controlling the RC system cooling capacity, the RC system surface temperature, the indoor RH, the space operative temperature, and zoning the systems accordingly will help in the process of creating a thermally comfortable environment, and will affect the building’s energy consumption, cost, and the system’s integrity.

4.5.4 RC system physical properties (EnV4)

The physical properties of the RC system play an important role in determining the final performance of the space where the system is installed. The physical properties of the RC system vary from one situation to another depending on the space cooling loads, space function, and space geometry. Three properties are discussed in this research: the dimensions of the cooled surfaces, location of the cooled surfaces, and the finish material of the cooled surfaces. For these the design decision will affect the space's thermal environment, the acoustical environment, the visual environment, and the spatial environment. Figure 4.13 shows the influence map of the physical properties.

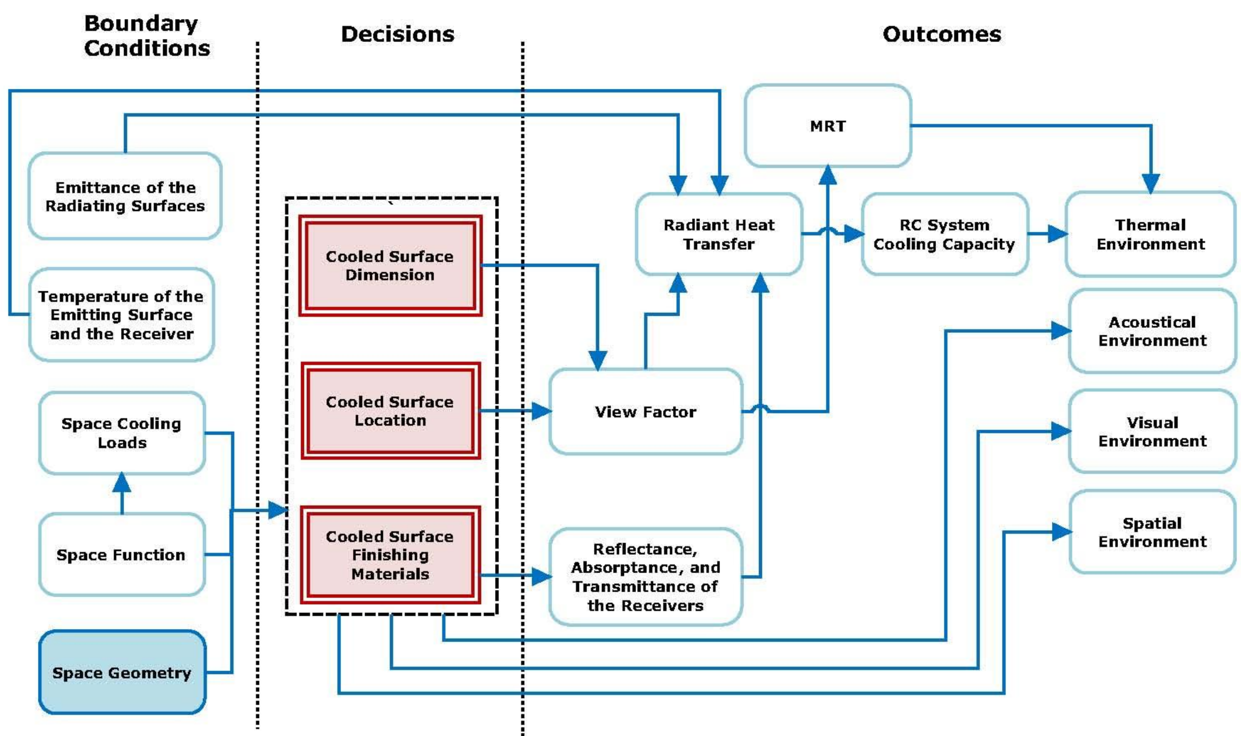


Figure 4.13. Influence map of RC system physical properties (EnV4)

Discussion:

a) The dimensions of the cooled surface are a major variable in the view factor calculations, see section 3.1.2.3.7. If the cooled surface is at certain distance from the heat source, the larger its area the larger the values of radiation heat transfer and the lower the MRT in the cooling mode. Those two values affect the thermal environment in the space.

b) Another factor affecting the view factor is the location of the cooled surface with regards to the space heat source. In general, the view factor of the chilled slab system is lower than for the RCCP system. This is valid if the RCCP is installed in spaces with normal ceiling height.
c) The thermal properties of the cooled surface finishing material will affect the radiant heat transfer between the heat sources and the cooled surface. These properties include the reflectance, the absorptance, and the transmittance of the cooled surface.
d) The physical properties of the RC system will also affect the space's acoustical environment, the visual environment, and the spatial environment as discussed in section 4.6.

Conclusion:

Determining the physical properties of the RC system is an integrated decision between the architect and the HVAC engineer. These decisions depend typically on a) the space function, as this will affect the location of the cooled surface, its dimensions, and its finishing material (See the discussion on (ExV4)), b) the space cooling loads, as the cooled surface dimension has a proportional relationship with the space cooling loads, and c) the space geometry, as this will affect the location of the cooled surface and its dimension.

The physical properties of the RC system will impact the space's acoustical environment, its visual environment, and its spatial environment. These impacts are explained in the discussion of (EvC3), (EvC4), and (EvC5).

4.5.5 Designers' and clients' goals and preferences (ExV1)

When considering the reasons for the infrequent application of RC systems in the U.S., Moore, Bauman, and Huizenga (2006) mentioned that "education appears to play a particularly critical role where experience with radiant cooling is lacking or limited". Stetiu (1998) added that another reason for the widespread use of RC systems in Europe while the system is rarely found in the U.S. is the "complex interaction of technical, economic, social, and cultural factors". Also, the climate in the U.S. could be added as another important constraint.

However, the case studies and the interviews revealed that the decision of the client to build an energy efficient building led the designing team to evaluate different cooling and heating systems. Computer energy modeling found that radiant systems have significant energy saving potentials. Also, different designers mentioned that the uses of radiant systems will a) create a better thermal environment, b) extend the natural ventilation mode in the building, and c) have the ability to improve the IAQ by having a separate ventilation system.

It could be concluded that the clients' goal of having energy efficient building is important for the RC system implementation. On the other hand, the designing team has to understand the system abilities and limitations to make its implementation successful.

4.5.6 Building codes and standards (ExV2)

Building codes and standards are important when installing any mechanical system in the built environment. In the case of RC systems, and because they have been seldom used in the U.S., their design and operating principles may be unfamiliar to code officials and their use may be limited by certain codes and building standards. These limits may translate as constraints to the decision-making process. Building codes and standards may not always directly govern decisions related to RC systems, but they may govern issues related to performance such as surface temperature, temperature asymmetry, humidity ratio, etc. Related codes are explained in the context of the framework.

The indoor built environment is governed by many codes and standards. However, this research focuses mainly on codes and standards related to the thermal environment and to IAQ. Other related standards and codes are discussed when required. Figure 4.14 shows the influence map for the codes and standards variable.

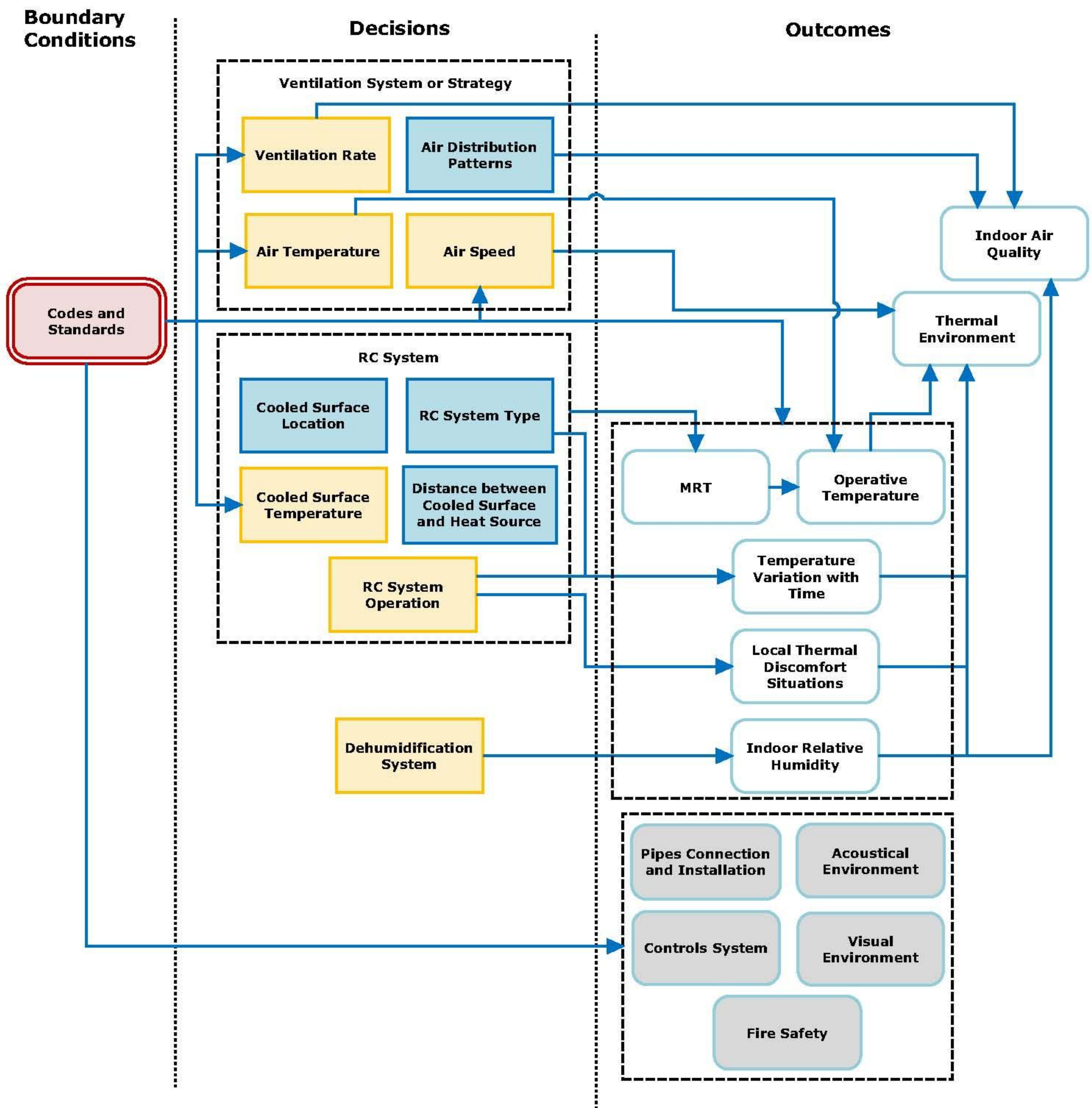


Figure 4.14. Influence map of codes and standards (ExV2)

Discussion:

Building codes and standards affect two main groups of variables; those which are related to the thermal environment **(ExV2a)** and those which are related to the IAQ environment **(ExV2b)**.

(V6a)

ANSI/ASHRAE Standard 55-2004 governs all issues related to thermal environment conditions for human occupancy as in the following:

Section 5.2.1 of the Standard discusses issues related to operative temperature, as explained in section 3.1.2.3.4 in this document.

Section 5.2.2 of the Standard discusses issues related to humidity limits, as explained in section 3.1.2.3.9 in this document.

Section 5.2.3 of the Standard discusses issues related to elevated air speed, as explained in section 3.1.2.4.3 in this document.

Section 5.2.4 of the Standard discusses issued related to local thermal discomfort, as explained in section 3.1.2.4 in this document.

Section 5.2.5 of the Standard discusses issues related to temperature variation with time, as explained in section 3.1.2.4 in this document.

(V6b)

ANSI/ ASHRAE Standard 62.1-2007 deals with issues related to ventilation for acceptable indoor air quality.

Table 6-1 of ANSI/ ASHRAE Standard 62.1-2007 specify the minimum ventilation rates in breathing zone for different spaces.

Conclusion:

Building codes and standards govern, mainly, engineers' decisions when designing and implementing RC systems. This is to help when creating acceptable thermal and IAQ environments for human occupation. Building codes and standards govern, in some cases, the range of the outcomes variables such as MRT, operative temperature, and indoor RH, etc. where these variables are the outcomes of many previous architectural and engineering decisions.

Architectural decisions such as choosing the RC system type, the distance between the cooled surfaces and the indoor heat sources, and the cooled surface location should be made to create thermal environment conditions as described in the relevant codes and standards.

4.5.7 Climate (Outdoor environment) (ExV3)

The outdoor environment conditions play an important role in determining some architectural design decisions. Outdoor conditions often suggest the selection of certain cooling, heating, and ventilation systems while prohibiting others. For example, implementing a RC system, or any conventional HVAC system, in hot and/or humid climates requires an air dehumidification strategy or similar strategy to prevent moisture intrusion through the building envelope to maintain the indoor humidity levels within desired limits, to eliminate the risk of condensation, and to maintain the required IAQ level of the conditioned space/building.

Where RC systems could be promoted as energy conserving, conventional air dehumidification is an energy intensive process. An important question concerns the quantity of the air that needs to be dehumidified and the efficiency of the dehumidification method.

Climate variables which can directly and indirectly affect the RC system implementation are mapped as shown in Figure 4.15.

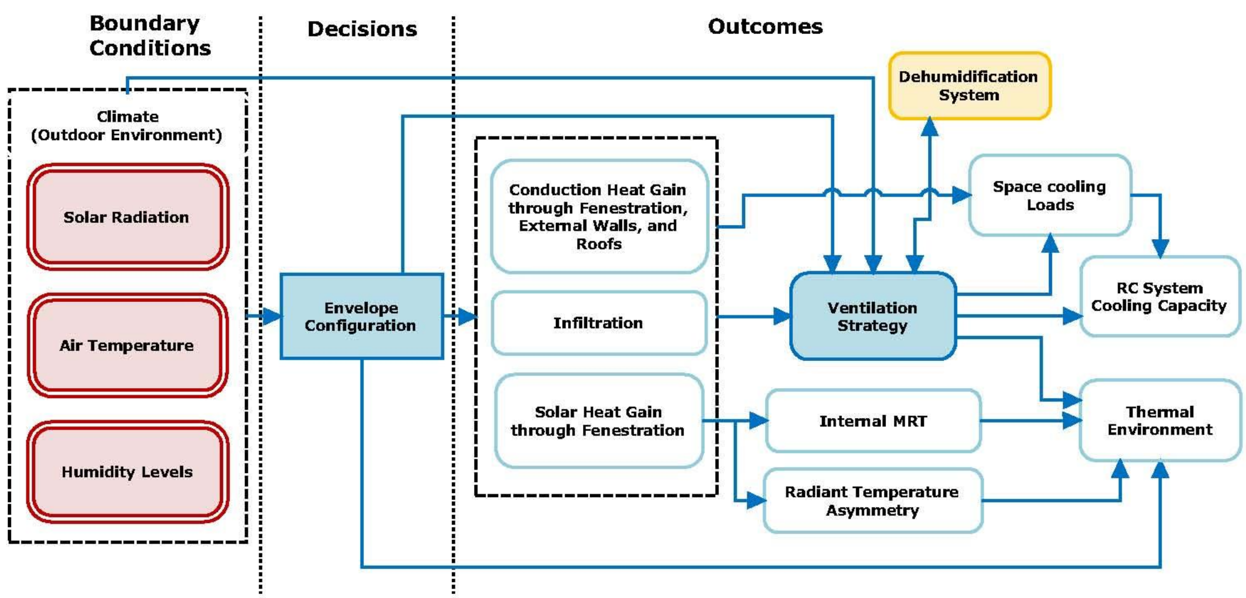


Figure 4.15. Influence diagram of the climate variables (ExV3)

Discussion:

The outdoor environment directly affects the envelope configuration. One of the architect's tasks is to design the enclosure to best respond to the outdoor conditions.

However, when considering RC systems there are at least three variables to consider; these are solar radiation, air temperature, and humidity level:

a) To avoid overheating, the conduction heat gain through fenestration, external walls, and roof should be minimized, allowing the RC system to meet the space loads (Hayter et al. 2001).The external conduction heat gain minimization includes applying many architectural design strategies such as double envelope systems and applying insulation materials.
b) To avoid overheating, the space/building envelope should be designed to minimize the direct solar gain with respect to other building performance mandates such as visual performance. Minimizing the direct solar heat gain will reduce the effect of radiant temperature asymmetry for occupants sitting near warm window surfaces. Architectural strategies may include applying shading devices or using reflective glass.
c) The ventilation strategy in spaces/buildings with RC systems should be designed to take care of the latent loads in addition to providing air for ventilation. Also, the ventilation strategy could be designed to take care of part of the sensible loads when necessary. Choosing the appropriate ventilation strategy is an architectural decision that could be affected by the envelope configuration, the external heat gain, and the outdoor climate conditions.
d) Behne (1999) showed through experimental investigation that the ventilation strategy will directly affect the cooling capacity of the system, as discussed in (ExV7).
e) In hot humid climate locations where the outdoor humidity levels are high, and if the infiltration rate is also high, then a dehumidification system is required. The dehumidification system is to minimize the space latent cooling loads.
f) The envelope configuration, i.e. curtain walls, masonry walls, etc. plays an important role in determining the infiltration and exfiltration rates and consequently the space cooling loads.
    i. In conditioned spaces, infiltration and exfiltration rates are important. Infiltration as defined in the *ASHRAE Handbook Fundamentals* (2009): “is the unintentional or accidental introduction of outside air into a building, typically through cracks in the building envelope and through use of doors for passage.” Exfiltration is the

reverse, the movement of air from inside to out. In hot and/or humid locations higher infiltration rates means larger cooling loads and unwanted humidity; this can be an issue for RC systems.

ii. Infiltration rates are directly related to the applied construction method and to the efforts to mitigate them. Infiltration rates are typically not zero but can be reduced using different strategies. One way to control infiltration in new buildings is to use air retarders.

iii. In dealing with infiltration, RC system should take care, mainly, of the sensible load, while the ventilation system should deal with the latent load. In hot humid climates, the envelope should be designed to minimize the moisture intrusion into the building. This will minimize the required latent cooling loads to be removed. Also, it will minimize the risk of having condensation on the cold surfaces.

Conclusion:

The outdoor climate conditions are important when designing RC systems. It is important to minimize the external heat gain through a properly configured building envelope to allow the RC systems to meet the space cooling loads and avoid thermal discomfort situations. Outdoor environment conditions also affect the decision of selecting the appropriate ventilation strategy.

4.5.8 Space function (ExV4)

The space function (program) is a critical variable when designing RC systems. Many function-related issues such as the cooling load (sensible cooling loads and latent cooling loads), the ventilation requirements, space usage rate (occupant load profile) should be considered early in the decision-making process.

Figure 4.16 maps the space function variables and their influence on the decision-making process.

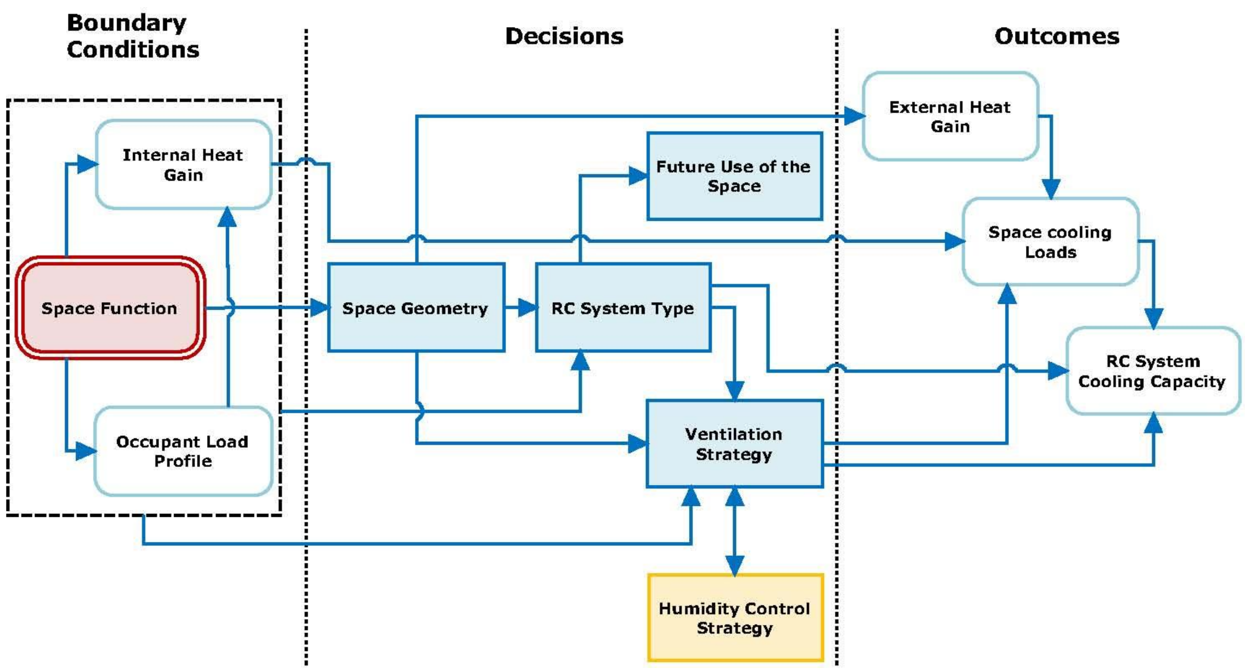


Figure 4.16. Influence diagram of the space function variable (ExV4)

Discussion:

a) The space function will typically have significant influence, from an architectural point of view, on the space/building geometry. Some of these spaces accept flexibility to change the program or/and the interior configuration such as office buildings and educational institutions, while others are less flexible to this change such as theaters and gymnasiums. The flexibility of the space will influence the RC system type selection, the ventilation strategy, and the external heat gain amount.

b) The space function as a pre-determined variable influences the internal heat load gain and will determine the nature of this load being steady or dynamic. RCCP systems are typically appropriate for dynamic cooling load spaces as they have quicker respond time than chilled slab systems. The space function will typically influence the amount of the internal heat gain. Figure 4.17 shows the typical metabolic heat generation for various activities.

	Btu/h·ft^2	met*
Resting		
Sleeping	13	0.7
Reclining	15	0.8
Seated, quiet	18	1.0
Standing, relaxed	22	1.2
Walking (on level surface)		
2.9 fps (2 mph)	37	2.0
4.4 fps (3 mph)	48	2.6
5.9 fps (4 mph)	70	3.8
Office Activities		
Reading, seated	18	1.0
Writing	18	1.0
Typing	20	1.1
Filing, seated	22	1.2
Filing, standing	26	1.4
Walking about	31	1.7
Lifting/packing	39	2.1
Driving/Flying		
Car	18 to 37	1.0 to 2.0
Aircraft, routine	22	1.2
Aircraft, instrument landing	33	1.8
Aircraft, combat	44	2.4
Heavy vehicle	59	3.2
Miscellaneous Occupational Activities		
Cooking	29 to 37	1.6 to 2.0
Housecleaning	37 to 63	2.0 to 3.4
Seated, heavy limb movement	41	2.2
Machine work		
sawing (table saw)	33	1.8
light (electrical industry)	37 to 44	2.0 to 2.4
heavy	74	4.0
Handling 110 lb bags	74	4.0
Pick and shovel work	74 to 88	4.0 to 4.8
Miscellaneous Leisure Activities		
Dancing, social	44 to 81	2.4 to 4.4
Calisthenics/exercise	55 to 74	3.0 to 4.0
Tennis, singles	66 to 74	3.6 to 4.0
Basketball	90 to 140	5.0 to 7.6
Wrestling, competitive	130 to 160	7.0 to 8.7

Figure 4.17. Typical metabolic heat generation for various activities
Source: (ASHRAE 2009)

Table 4.1 from Brown and DeKay (2001) provides some examples of the average values of heat generation for typical occupancies and building types. The values show the sensible and latent heat generation rates.

Table 4.1. Typical heat generation per person in occupational situations
Source: (Brown and DeKay 2001)

Degree of Activity	Typical Occupancy	Sensible Heat Gain		Latent Heat Gain	
		Btu/hr	Watts	Btu/hr	Watts
Seated at rest, Seated very light work	Theater	225-245	66-72	105-155	31-45
Moderately active office work, Walking slowly	Office, Bank, Hotel, Retail, Apartment, Drugstore	250	73	200	59
Sedentary work, Light bench work	Restaurant, Factory	275	81	275-475	81-139
Moderate dancing	Dance hall	305	89	545	160
Walking fast, Moderately heavy work	Factory	375	110	625	183
Bowling, Heavy work, lifting	Factory, Bowling Alley	580-635	170-186	870-965	255-283
Athletics	Gymnasium	710	208	1090	319

c) The current and the future use of the space should be well understood by the decision maker before implementing the RC system. For example, if a chilled slab system is to be implemented, this means floors cannot be covered with carpet and raised floor systems should not be used.

d) RC systems directly satisfy the sensible cooling loads and only indirectly handle some of the latent loads. Ventilation systems mainly are for IAQ purposes while they may also satisfy the latent loads. Accordingly, the amount of sensible cooling loads, latent loads, ventilation rates, and infiltration rates are directly related to the space function as well as other issues such as the space geometry. Therefore spaces with a wide range of cooling loads or with high occupancy densities will influence the decision-making process. They will influence the humidity control strategy, envelope configuration, and the RC system type selection.

e) On the other hand, the cooling capacity of RC systems is a potentially limiting variable, particularly when applied to unsealed spaces such as naturally ventilated buildings, or in spaces with variable occupancy densities such as auditoriums, where the RC system alone may not meet the cooling load. Therefore consideration for the function and program of the space must be part of the decision-making process.

4.5.9 Space characteristics (ExV5)

The space characteristics play a major role in the decision to implement a RC system or not. Space variables include ceiling height and the glazed areas. The space variables can be modified and altered by the architect as the space requires. Figure 4.18 maps the space variables.

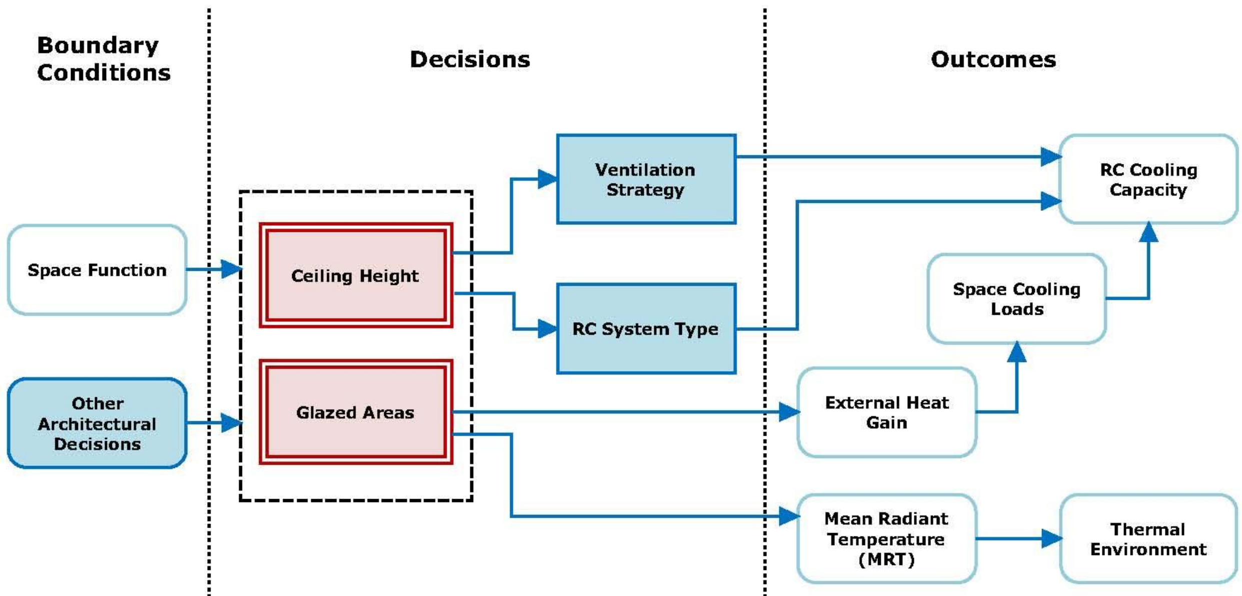


Figure 4.18. Influence map of the space characteristics (ExV5)

Discussion:

As revealed from the analysis of the relevant sources of knowledge, the space variables include two architectural variables; the space ceiling height (**ExV5a**) and the glazed areas in the space (**ExV5b**). They are influenced mainly by the space function and other architectural decisions such as aesthetics. These characteristics affect the design and the implementation of the RC system as in the following:

(ExV5a)

a) The ceiling height of the space affects the type of the RC system. Typically, in high ceiling spaces, chilled slab systems are used. RCCP systems in high ceiling spaces are ineffective as the view factor value is small and therefore the RCCP cooling effect will be very limited. There is no solid value for the height of 'high ceilings', some experts explained 'normal ceiling height' by the height of common office, classrooms, and workshops building space which are under 13 feet.
b) The ceiling system height also affects the ventilation strategy and the ventilation mechanical system design. If the space ceiling is 'high', a displacement ventilation system is recommended over other systems for many reasons including the relatively low energy consumption.

(ExV5b)

a) When implementing a RC system the glazed areas should be designed carefully to minimize the external heat gain of the space, thus enabling the RC system to meet the space cooling loads and provide a thermally comfortable environment.
b) Also, the glazed areas should be designed to prevent the existence of warm surfaces in the space which may create thermal asymmetric situations and cause local thermal discomfort.

Conclusion:

Normal ceiling height is defined to be about 9-13 feet. In high ceiling spaces the RCCP system and the chilled slab with active ceiling sides are ineffective due to the small view factor value. Also, in high ceiling spaces, displacement ventilation is recommended. Glazed areas should be designed to minimize heat gain and prevent radiant asymmetric situations.

4.5.10 Construction system type (ExV6)

The construction system (space/building skeleton system) will affect the RC system type selection. As explained previously, there are many RC system configurations, and not all are suitable for all construction systems. Construction system type variables are mapped in Figure 4.19.

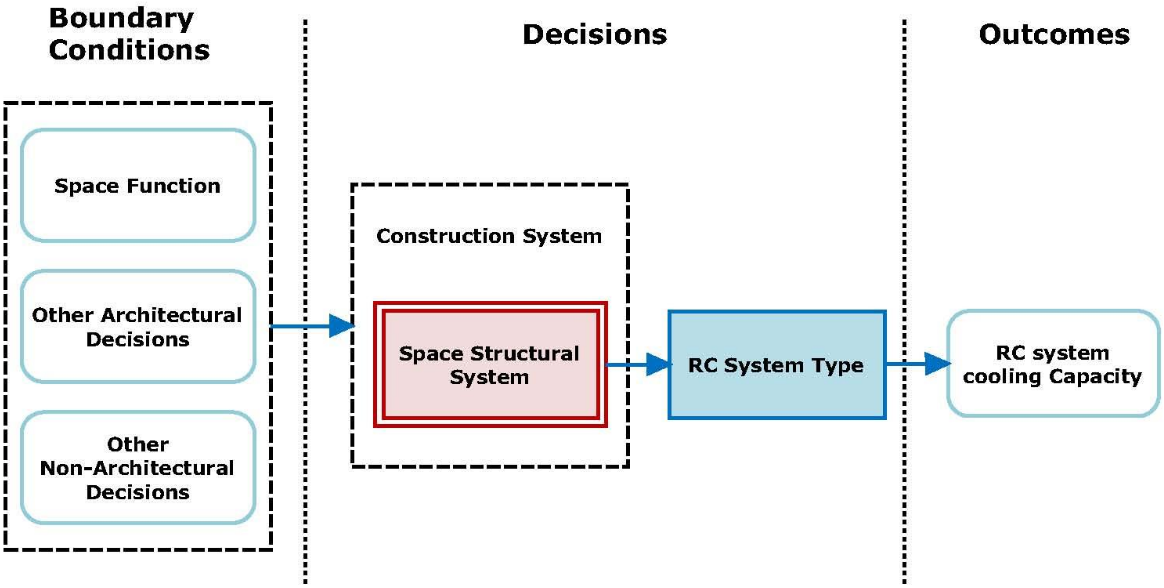


Figure 4.19. Influence map of the construction system type variable (ExV6)

Discussion:

a) The decision to choose a particular building structural system such as concrete post and beams, wood frames, or steel, is derived from many other variables such as the space function, aesthetic quality, cost, site conditions, etc. However, making this decision will typically affect the RC system type. For example, the chilled slab system usually is integral with a concrete slab and does not work as effectively in wooden floor buildings. On the other hand, the RCCP system can be implemented, for example, in wooden structure buildings as the building structural system does not affect its implementation.

b) As explained in section 3.1.1.1.1, different RC systems have different cooling capacities and other criteria must be understood before their implementation.

Conclusion:

The building structural system can constrain the selection of the RC system. Chilled slab systems are usually integrated with concrete slabs, while RCCP systems do not require any special structural system to be implemented.

4.5.11 Ventilation system (ExV7)

Conventional HVAC systems provide cooling, heating, and ventilation. For RC systems in non-residential buildings, both space conditioning (thermal control) and ventilation must be considered. RC systems do not provide ventilation nor do they directly take care of the latent cooling, and therefore require ventilation as an additional system. However, the combining of the two systems does not necessarily optimize the advantages of both systems.

Outdoor air can be introduced to the space naturally, using a neutral ventilation strategy, or mechanically, using a mechanical ventilation system such as mix ventilation system and displacement ventilation system. Air is needed in the conditioned space for ventilation purposes, providing acceptable IAQ, and for thermal comfort purposes. The influence map of the ventilation system when implementing a RC system is shown in Figure 4.20.

.

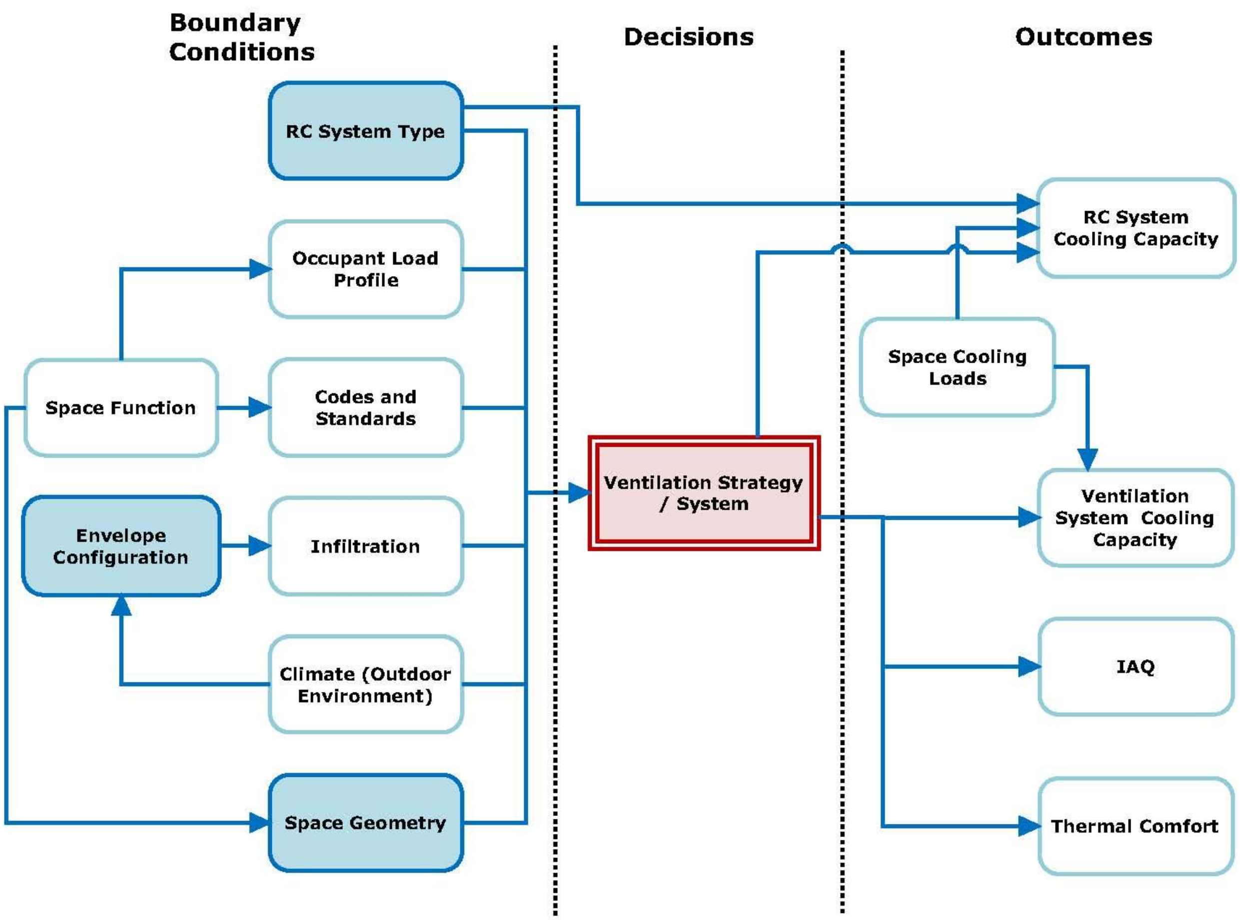


Figure 4.20. Influence map of the ventilation strategy/system when implementing RC system (ExV7)

Discussion:

a) Space function, occupant load profiles, codes and standards, infiltration rate, outdoor environment, and the space geometry have great influence on selecting the appropriate ventilation system/strategy.

b) ASHRAE Standard 62.1-2007 regulates the "minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to avoid adverse health effects"(ANSI/ASHRAE 62.1 2007).

c) The selection of the RC system type influences the ventilation system selection and design. With chilled slab systems, an underfloor ventilation system is typically not practical.

d) The space geometry may also restrict the ventilation strategy and system characteristics as explained in the discussion of the space variables (ExV5).

e) The adopted ventilation strategy may affect the envelope configuration and its properties. For example, naturally ventilated buildings/spaces will typically allow operable windows with occupants' control, whereas putting the conditioned space under positive pressure to minimize the moisture intrusion will impose restrictions on openings and the way they operate.

f) The ventilation strategy has a direct effect on the space cooling loads and on the RC system cooling capacity:
   i. If the introduced air is relatively dry and cool, this will minimize the space cooling load by not adding moisture to the conditioned spaces and by not raising the indoor air temperature, thus minimizing the need for indirect (convection) cooling effect of the RC system.
   ii. The cooling capacity of the RCCP could be enhanced 5% to 35% when using mixed ventilation under normal operation temperatures (Jeong and Mumma 2003).
   iii. The combination of RCCP and mixed ventilation can affect the IAQ while providing a good thermal comfort situation (Behne 1999), see section 3.1.2.5.1 for more details.

g) The ventilation system is to help the RC system, when required, meeting the space cooling loads. In some cases the RC system cooling capacity does not meet the space cooling loads, thus a supplementary ventilation system is required to provide a thermally comfortable environment.

Conclusion:

A ventilation system is typically required when implementing a RC system. This system is to provide the required air for ventilation and to maintain acceptable IAQ as defined by the standards and codes. Some RC systems such as chilled slab limit the options of the ventilation system. In the situation where the RC system does not meet the space cooling loads alone, a supplementary ventilation system is required to maintain an acceptable thermal environment.

4.6 System Evaluative Categories

If the decision is taken to implement a RC system in the space, it is important to evaluate the system implementation in the light of the building mandates defined previously in section 3.1.2.2. One of the motivations for this research is to bridge the gap between the architectural discipline and other disciplines involved in the decisions of creating the built environment. Though the architect is mainly concerned with the spatial quality of the space, other systems used to achieve the desired level of performance should be acknowledged. However, the decision maker should acknowledge that different spaces have different functions and different priorities. There is no single decision path to meet all of these priorities in the same space; trade-offs are important and critical.

The evaluation of the building performance can be predicted using different methods and procedures. While numerical simulation strategies (computer modeling) typically have relatively low cost and can provide accurate results (Novoselac and Srebric 2002), some building mandates are qualitative and cannot be simulated. Also, in the architectural domain, understanding the concepts behind these tools is more important as the results of these numerical strategies are, typically, focused and limited. At the same time, the complex relations between different mandates makes following guidelines for a specific system as an independent system not appropriate (Novoselac and Srebric 2002; Moore 2008), and thus simulation tools would provide a more comprehensive perspective of the predicted performance.

The systematic literature review analysis, the case studies, and the interviews revealed that there are five main categories against which to evaluate the performance of the RC system: thermal comfort, IAQ, the acoustical environment, the visual environment, and the spatial environment. As the RC system is discussed as an alternative cooling strategy to conventional HVAC systems, the thermal comfort and the IAQ are discussed in more detail.

The influence of RC system implementation is divided into three types:

Direct impact influence: variables for which their values are affected directly by the RC system implementation such as MRT.

Indirect impact influence: variables for which their values have to be changed or controlled within certain limits to accommodate the RC system implementation such as RH.

Minimum impact influence: variables for which their values will stay the same with or without the RC system implementation.

4.6.1 Thermal comfort (EvC1)

In general, several studies show that the implementation of RC systems could provide a better thermal environment when compared to conventional all-air HVAC systems (Feustel and Stetiu 1995; Tian and Love 2006; Henze et al. 2008; Hodder et al. 1998; Imanari, Omori, and Bogaki 1999; Kitagawa et al. 1999; Loveday et al. 2002; Memon, Chirarattananon, and Vangtook 2008; Novoselac and Srebric 2002; Vangtook and Chirarattananon 2006).

A RC system is primarily a cooling strategy, where the main purpose of the system installation in a space/building is to provide and enhance thermal comfort. Based on the previous analysis the implementation of a RC system affects the thermal environment as presented in Figure 4.21.

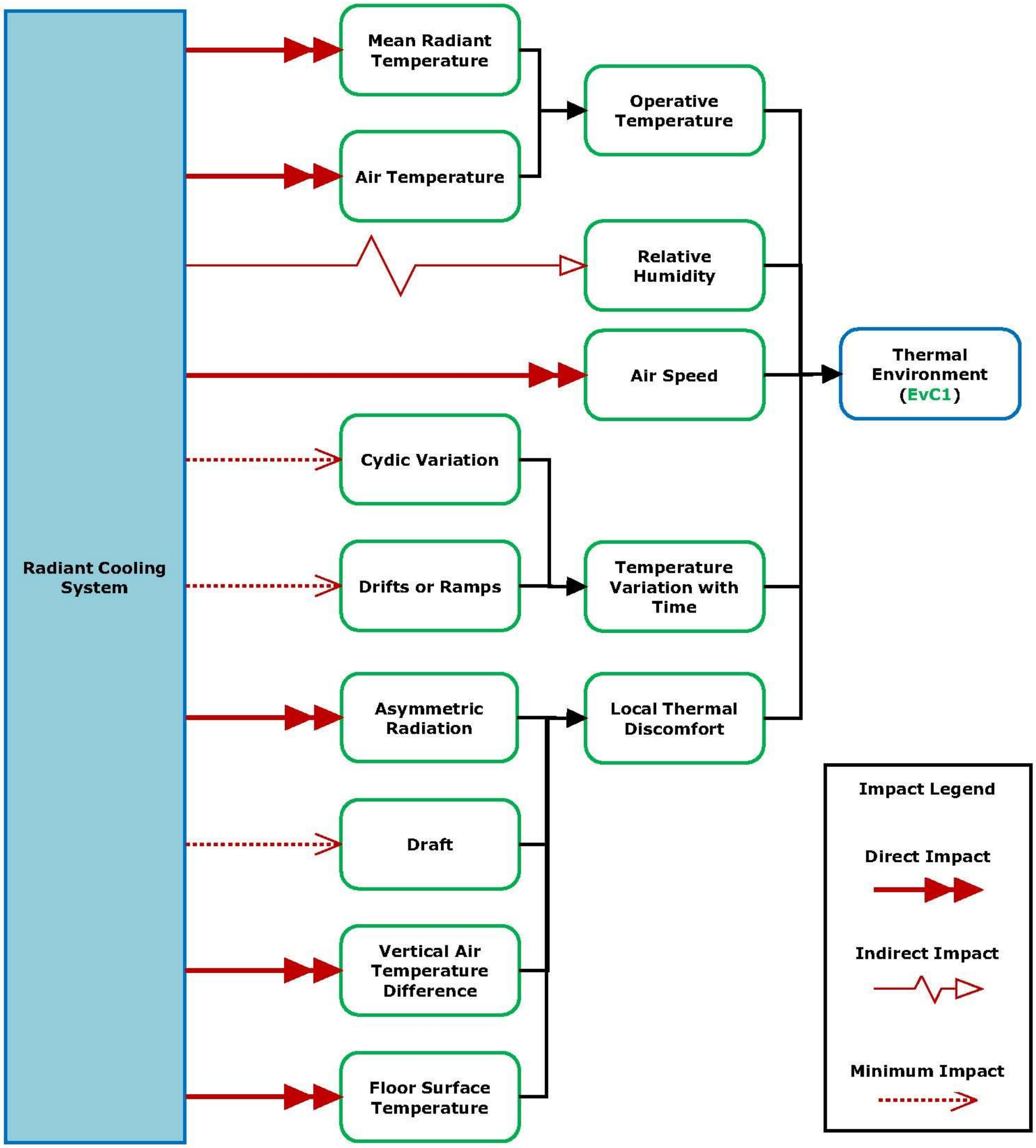


Figure 4.21. Thermal comfort evaluative category (EvC1)

Discussion:

Figure 4.21 presents how the installation of a RC system affects the variables associated with thermal comfort. The RC system directly impacts some variables such as MRT, or might have an indirect impact on other variables such as the indoor relative humidity, or might have a minimum impact on variables such as draft. These relations are explained in the following points:

a) Direct impact

i. Mean Radiant Temperature (MRT)

MRT is the key variable when designing and implementing a RC system. Standards such as ANSI/ASHRAE 55-2004 have established a range of limits for the operative temperature (combination of MRT and air temperature).

The view angle between the occupants and the radiant cooling surfaces, space geometry, material properties, window placement, and occupant location and orientation play an important role in determining the MRT value.

However, in real situations RC systems are not designed to maintain the space at certain MRT although they have significant impact on its value, (Andreas Limberg, personal communication, April 15, 2011; Fred Bauman, personal communication, April 15, 2011). Jeong and Mumma (2006) mentioned that the RCCP system would reduce space MRT about 2 °F to 4 °F when compared to spaces without RCCP systems. Lower MRT has positive effect on thermal comfort sensation of the occupants (Novoselac and Srebric 2002).

ii. Air temperature

The RC system is a heat sink and the heat exchange between the cooled surfaces and heat sources in the space is by radiation. Heat from air close to the cooled surfaces will be extracted by convection and thus helps cool the space by convection. This phenomenon is more obvious in RC ceiling systems and in mechanically ventilated spaces.

The air temperature in the space with a RC system could be set at about 2 °F higher to obtain the same thermal comfort as with conventional all-air systems, as the operative temperature is the average value of MRT and air temperature as explained in section 3.1.2.3.4.

The air temperature distribution could be affected in spaces with RC systems as explained in point 3.1.2.5.1.

iii. Asymmetric radiation

The glazing areas in the envelope should be designed a) to avoid being hot in summers and b) to reduce the amount of direct sunlight penetrating the space to minimize the risk of having uncomfortable asymmetric thermal radiation spots.

With the existence of a RC system in the space, the chances for an asymmetric situation are more likely to happen if not designed properly. Novoselac and Srebric (2002) mentioned that uncomfortable asymmetric thermal radiation is not likely to happen due to the temperature differences between the RCCP and the floor surfaces. People are less sensitive to asymmetric radiation cased by cooled ceiling than that caused by warm ceiling.

iv. Floor surface temperature

Since RC systems could use the floor as the cooled surface, the floor temperature should be within the range specified by standard ANSA/ASHRAE 55 considering the space function and the occupancy conditions (being seated or walking, wearing shoes or with bare feet).

v. Vertical air temperature

Spaces with RC systems can experience vertical temperature gradients. This temperature gradient depends mainly on the combination of the RC system type and the ventilation system used in the space. The portion of the cooling load removed by the RC system to the cooling load removed by the ventilation system is another major factor (Novoselac and Srebric 2002). However, the acceptable range of temperature gradient is governed by ANSI/ASHRAE Standard 55-2004 as explained in section 3.1.2.4.3.

Experimental and numerical results from different studies showed that when the air temperature differences, in the occupied zones 4 inches and 67 inches above the floor, are within the allowable range, this will not cause any thermal discomfort sensations (Olesen 1997; Alamdari et al. 1998; Behne 1999; Novoselac and Srebric 2002).

vi. Air speed

Hodder et al.(1998) showed that lowering the RCCP system surface temperature would increase the system cooling capacity and thus increase the downward air flow motion caused by the negative buoyancy. However, this air motion is still in the acceptable ranges so as not to cause draft. This conclusion is confirmed by other research studies (Loveday et al. 2002; Novoselac and Srebric 2002).

b) Indirect impact

i. Relative humidity (RH)

When installing RC systems it is important to keep the cooling surfaces at all times above the dew-point temperature of the space to avoid possible condensation on the cooled surfaces. Indoor humidity control could be achieved through many techniques as discussed in section 3.1.2.3.10. Kitagawa et al.(1999) mentioned that higher humidity levels in spaces with RC systems result in warmer sensations.

c) Minimum impact

The following variables will be barely affected by the installation of RC systems in the space. However, they may be affected by other systems. They are cydic variation, drifts or ramps, and draft.

4.6.2 IAQ (EvC2)

Decoupling the ventilation system from the cooling/heating system is the main feature of RC systems. Conventional all-air systems are typically responsible for maintaining IAQ in addition to heating and cooling tasks. RC systems do not provide air for cooling nor for ventilation, and thus a supplementary system is needed for ventilation. As explained in section 3.1.2.5.1, any combination of RC and ventilation systems could be used in the space, with regards to other design issues, as long as the interactions between both systems are well understood.

Indoor air quality is characterized generally by the following three factors: physical factors which include operative temperature and humidity, mechanical factors which include air speed, ventilation rate, and distribution (ventilation efficiency), and chemical factors which include mass pollutants and energy pollutants from inside and outside. Installing RC systems will have impact on these factors as shown in Figure 4.22.

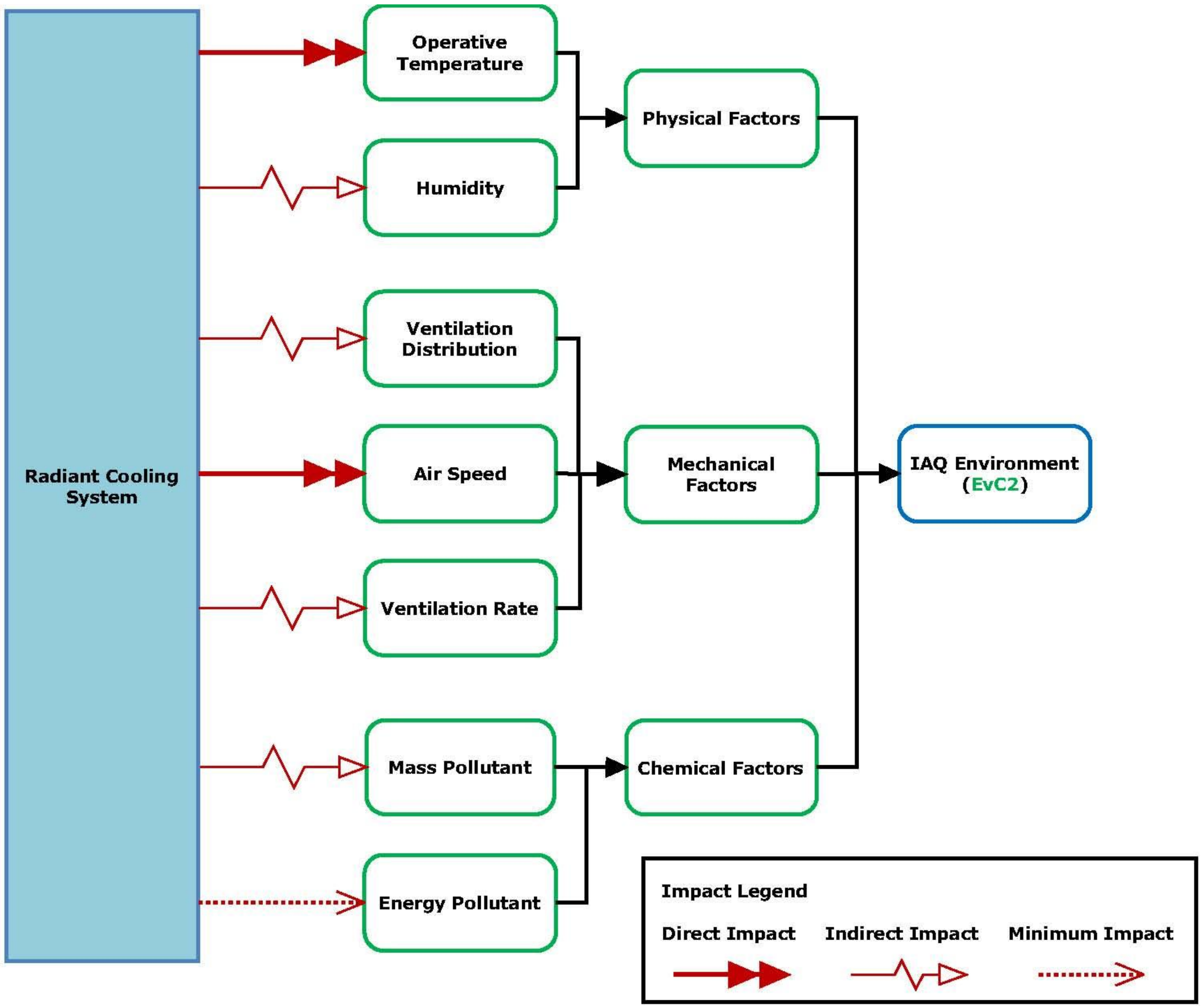


Figure 4.22. Indoor Air Quality (IAQ) evaluative category (EvC2)

Discussion:

Figure 5.25 presents the possible impacts of installing a RC system on the IAQ environment. These impacts are explained in the following points:

a) Direct impact

i. *Operative temperature*

As discussed in section 3.1.2.3.6, the MRT in spaces with RC systems will be about 2 °F to 4 °F lower than in spaces without RC systems, thus the space air temperature can be set at 2 °F higher to achieve the same operative temperatures as in spaces with all-air systems.

ii. *Air speed*

As discussed earlier in section 4.6.1.

b) Indirect impact

i. *Indoor relative humidity*

The main tasks of supplementary ventilation systems are a) to take care of the space latent cooling loads, b) to keep the humidity levels within the limits to prevent possible condensation and mold growing, and c) to provide the needed air for ventilation. This may impose more constraints on the indoor RH than what is mentioned in ASNI/ASHRAE Sandard 55-2004.

ii. *Ventilation distribution*

The ventilation distribution includes a) air introduction; how the air is introduced to the space, b) air flow; how the air is moving within the space, and c) air removal; how the air is removed from the space. These three points are governed by the ventilation system type and configuration within the space. As explained in section 3.1.2.5.1 the combinations of RC and ventilation systems are limited by the in depth understanding of their interactions.

iii. *Ventilation rate*

When using a RC system and DOAS the quantity of air to be treated, for ventilation and latent cooling, is about 20% of that for conventional all-air systems (Mumma 2002). However, the ventilation rate is affected a) in cases where the RC system cannot meet the sensible cooling loads, the mechanical ventilation rate could be increased to help the RC system meet the space cooling loads, b) when the space cooling load is suddenly increased, increasing the ventilation rate will help maintain the space within the comfort zone.

iv. Mass pollutant

Contaminant concentrations in the occupied zone are a factor for IAQ. The contamination concentration, which is also called dimensionless concentration or contaminant removal efficiency, is estimated as using equation 4.1.

$$\mu = C_i - C_{SA} / C_{EA} - C_{SA} \qquad \text{Eq. (4.1)}$$

Where:
C_i *: the local contaminant concentration*
C_{SA} *: the contaminant concentration in supply air*
C_{EA} *: the contaminant concentration in exhaust air*

For perfect mixing ventilation the contaminant concentration in the exhaust air tends to equal the local contaminant concentration and μ is 1.0. The variance in contamination concentration depends on the spatial distribution of the contaminant sources and the air flow pattern.

The contamination distribution is a very critical issue when using RCCP systems coupled with a displacement ventilation system. Displacement systems try to push the contaminants above the occupied zone, while the downward airflow from the RCCP push them down. Achieving a balanced situation is possible by carefully designing of both systems.

c) Minimum impact

The energy pollutant variable will be slightly affected by the installation of the RC system in the space.

4.6.3 Acoustic performance (EvC3)

The built environment should be designed to assist in defining the meaningful sound signals required for communication and orientation, to assure that these sounds are perceived against an acceptable background noise, and to minimize noise level (Flynn et al. 1992). To evaluate the acoustic performance in a given space the following factors should be analyzed: sound absorption, sound reflection, and sound transmission. Implementing a RC system in a space means utilizing relatively large surfaces of the room interior for heat exchange; this typically will impact the previous factors as shown in Figure 4.23:

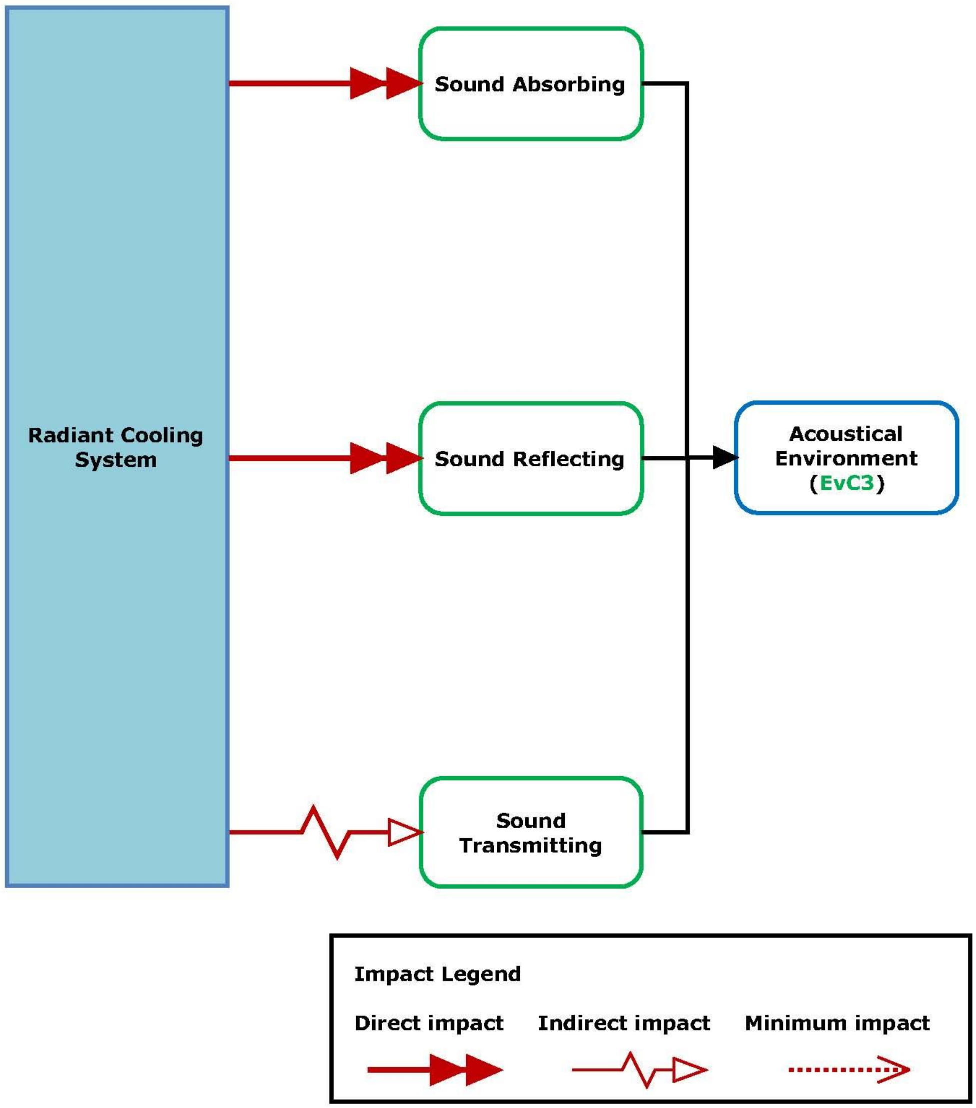


Figure 4.23. Acoustical environment evaluative category (EvC3)

Discussion:

Figure 4.23 presents the possible impacts of a RC system on the acoustical environment. These impacts are explained as follows:

a) Direct impact

i. Sound absorbing and sound reflecting

If the material's sound absorbing coefficient is high, the reflected sound waves will be low.

The ideal mean Noise Reduction Coefficient (NRC) for materials in a space is related mainly to the space function as Table 4.2 shows:

Table 4.2. Mean noise reduction coefficient and space function
Source: (Flynn et al. 1992)

Mean Noise Reduction Coefficient for Materials in the Space (Ā)	Suitable Use
0.4 - 0.5	Theater, lecture halls, and other spaces where use of electronic sound is needed such as recording studios
0.25 - 0.4	Medium activity spaces such as elementary classrooms, corridors, general offices
0.25	Low activity spaces such as private offices and small stores
0.05 – 0.25	Spaces where oral communication predominates as an activity such as conference rooms
0.05	Gymnasiums and large churches

When calculating the total room absorption using equation 4.2, the location of the sound absorbing-materials have no significant impact (Egan 1988).

$$a = \Sigma S \alpha \qquad \text{Eq. (4.2)}$$

Where:
a: total room absorption (sabins)
S: surface area (ft²)
α: sound absorption coefficient at given frequency (decimal percent)

In addition to controling the total room absorption value, reverberating sounds should be considered as they may affect the clarity of the communicating signal.

Reverberation time can be controlled by changing the room volume, the absorbing/reflecting characteristics of surfaces and finishes, and the density of room occupancy as equation (4.3) shows:

$$T_r = 0.049\ V / \Sigma\ S\alpha \qquad \text{Eq. (4.3)}$$

Where:
T_r: reverberation time (s)
V : the room volume (ft^3)
$\Sigma\ S\ \alpha$: total room absorption (sabins)

For chilled slab systems: in this case, sound-absorbing materials could be installed on the walls or on the ceilings if the ceiling sides are not used as a cooling surface. The active surface sides (floors or ceilings) have to be left uncovered or with minimum cover for better heat exchange and thus better thermal environment.

For RCCP systems: Conroy and Mumma (2001) suggest that RCCP systems can be purchased with perforations in the surfaces to allow sound to pass through the panel and be absorbed by the insulation above the panels. They added that the fin perforation can be varied depending on the expected acoustical performance in the space. Conroy and Mumma (2001) in a study to compare the reverberation time in a 66,000 ft^3 lecture hall with perforated RCCP systems and with normal acoustical ceiling tiles, they found, as shown in Figure 4.24, that the reverberation times follow along slightly higher than the normal acoustical ceiling tiles. The deviation becomes more noticeable with higher sound frequencies but is still acceptable for a wide range of space functions as Table 4.3 shows.

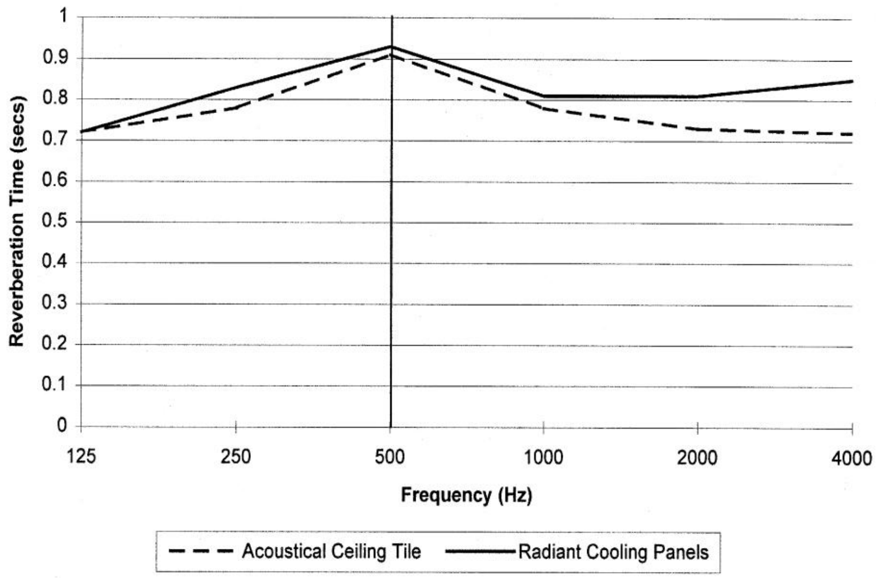


Figure 4.24 Comparison of the acoustical performance of perforated RCCP and acoustical ceiling tiles
Source: (Conroy and Mumma 2001)

Table 4.3. Reverberation time and listening conditions
Source: (Flynn et al. 1992)

Reverberation time (seconds)	Listening Conditions
Below 1.0	Optimum for speech
1.0 – 1.5	Good for speech and fair for music
1.5- 2.0	Fair for speech and good for music
Above 2.0	Poor for speech and fair for most music

b) Indirect impact

i. *Sound transmission*

Sound transmission between spaces associated with conventional HVAC systems will be reduced to the minimum or even eliminated when using RC systems. The supplementary ventilation system will deliver 20% of the air from conventional all-air systems, this means smaller duct sizes and reduction of sound transmission and reduction of equipment noise.

On the other hand, the conventional sound transmitting paths (airborne sounds) in the built environment, i.e. through plenum and partitions, is related to architectural decisions related to the spatial configurations and the RC system implementation has minimal impact on this issue.

4.6.4 Visual performance (EvC4)

In general, built spaces should be designed with adequate levels of light so occupants can do their activities without any discomfort related to the visual environment. Light can be introduced to the space naturally (daylighting), or artificially using electrical lighting systems, or using both strategies. Natural light is typically introduced through the space envelope (walls and roofs), where artificial light is typically integrated with the ceiling system.

When considering a RC system there are two main points to consider:

a) There are two major RC system types: RCCP systems which are integrated with the space ceiling system, and chilled slab systems which may use the floor, or the ceiling, or both. This means chilled slabs with active floor sides do not interact with any lighting systems, while the other RC systems have to be integrated with the artificial lighting system.
b) RC system implementation requires designing the envelope system to minimize external heat gain and prevent the hot surfaces, which will affect the amount of daylight introduced to the space and potentially contribute to lower daylight factors.

There are three major factors that affect the indoor visual environment: illuminance (lighting level and distribution), luminance ratios (brightness, contrast, and glare), and color rendition. Implementing a RC system in the space could impact these variables differently as shown in Figure 4.25.

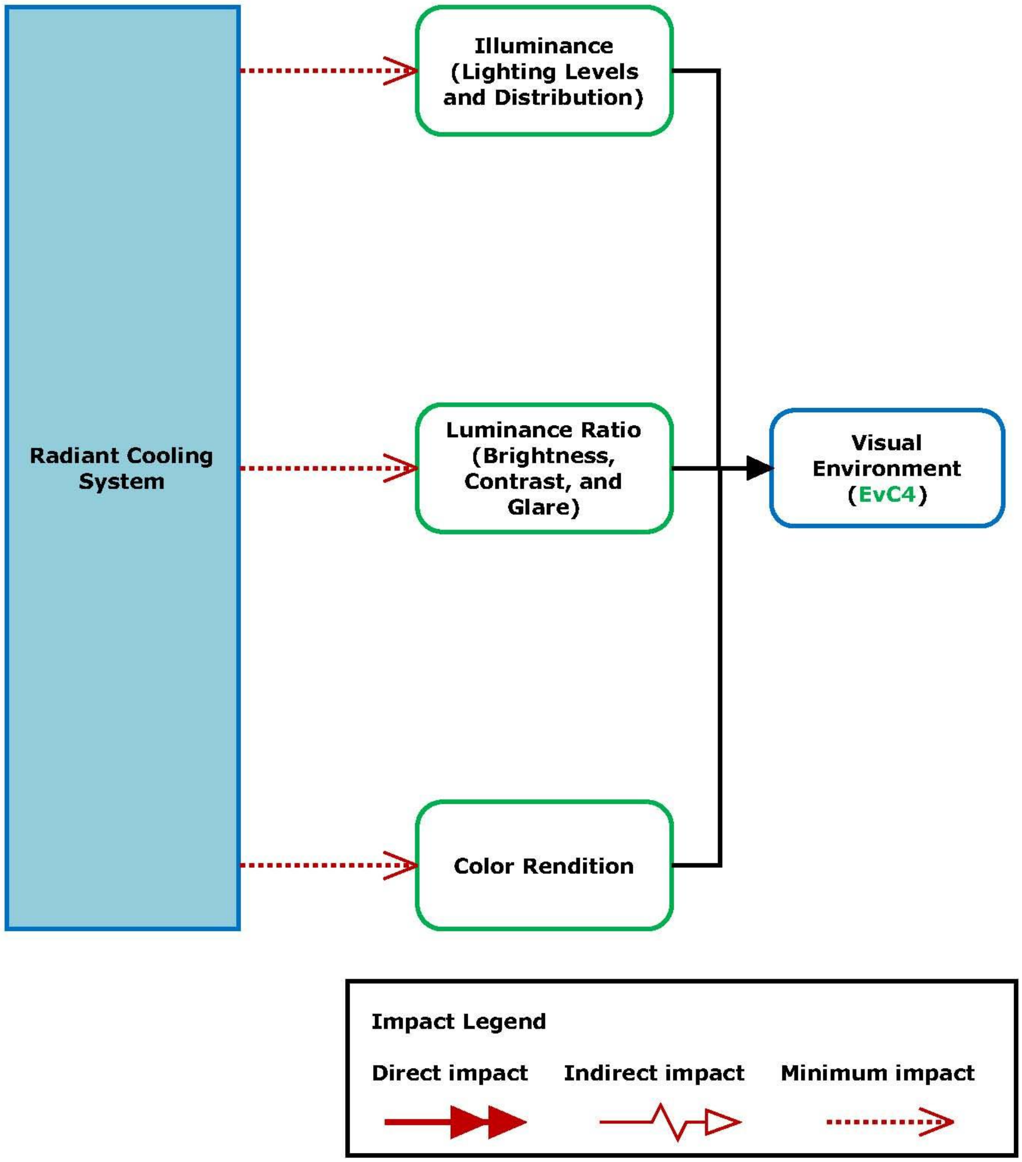


Figure 4.25. Visual environment evaluative category (EvC4)

Discussion:

Figure 4.25 presents the possible impacts of installing a RC system on the visual environment. These impacts are explained in the following:

a) Minimum impact

i. Illuminance (lighting levels and distribution)

Artificial lighting systems and RCCP systems: RCCP systems typically do not cover the whole ceiling area, as the coverage area is related to the total system cooling capacity needed in the space. Conroy and Mumma (2001) explained that for typical office spaces a RCCP system will occupy only one third of the ceiling surface area; this means that the artificial light system could be installed without conflict. Current RCCP system manufacturers have developed panel modules to support other functions such as sound absorption and embedded lighting fixtures.

Daylighting and RCCP systems: an advantage of the RCCP system that it does not require the same plenum space as in the case of conventional HVAC systems. This may be utilized to increase the ceiling height, within limits, and introduce more daylight to the space. On the other hand, the glazed area should be designed to minimize heat gain and this may constrain daylighting strategies.

Artificial lighting system and chilled slab systems: if the thermally active surface in the chilled slab is the floor side, then there is no conflict with both systems' implementations. If the thermally active surface of the chilled slab is the ceiling side, then the artificial lighting system can be installed as desired. Artificial lighting systems are typically lightweight and have a small surface area and they will not block the line of sight between the heat source and the chilled ceiling.

Daylighting and chilled slab systems: if daylight is introduced through the envelope then there is no conflict between both systems. However, if the daylight is introduced through skylights, this will limit the available area for the chilled slab if using ceiling sides.

In conclusion, when carefully designed the RC system implementation does not conflict with the lighting system in the space (natural or artificial) and thus the RC system will have minimum impact on the lighting levels and distribution.

ii. Luminance ratio (brightness, contrast, and glare)

For better radiant heat exchange, the line of sight between the RC system surfaces and the heating source has to be clear. This means exposing the surfaces of the system all times. The finish material of the RC system could be treated, without adding any insulation material, to avoid causing glare. Thus, the implementation of the RC systems will have minimum impact on the luminance ratio inside the space.

iii. Color rendition

This issue is related directly to the source of the light and is only slightly affected by an exogenous factor.

4.6.5 Spatial performance (EvC5)

Designing for the spatial environment includes designing for individual spaces and furnishings to provide the best support for the individual activity, the aggregation of individual spaces to best support needs of activities as a whole, circulation, space flexibility, convenience and services, and design for amenities. Installing a RC system in the space will impact these issues at different levels as Figure 4.26 shows:

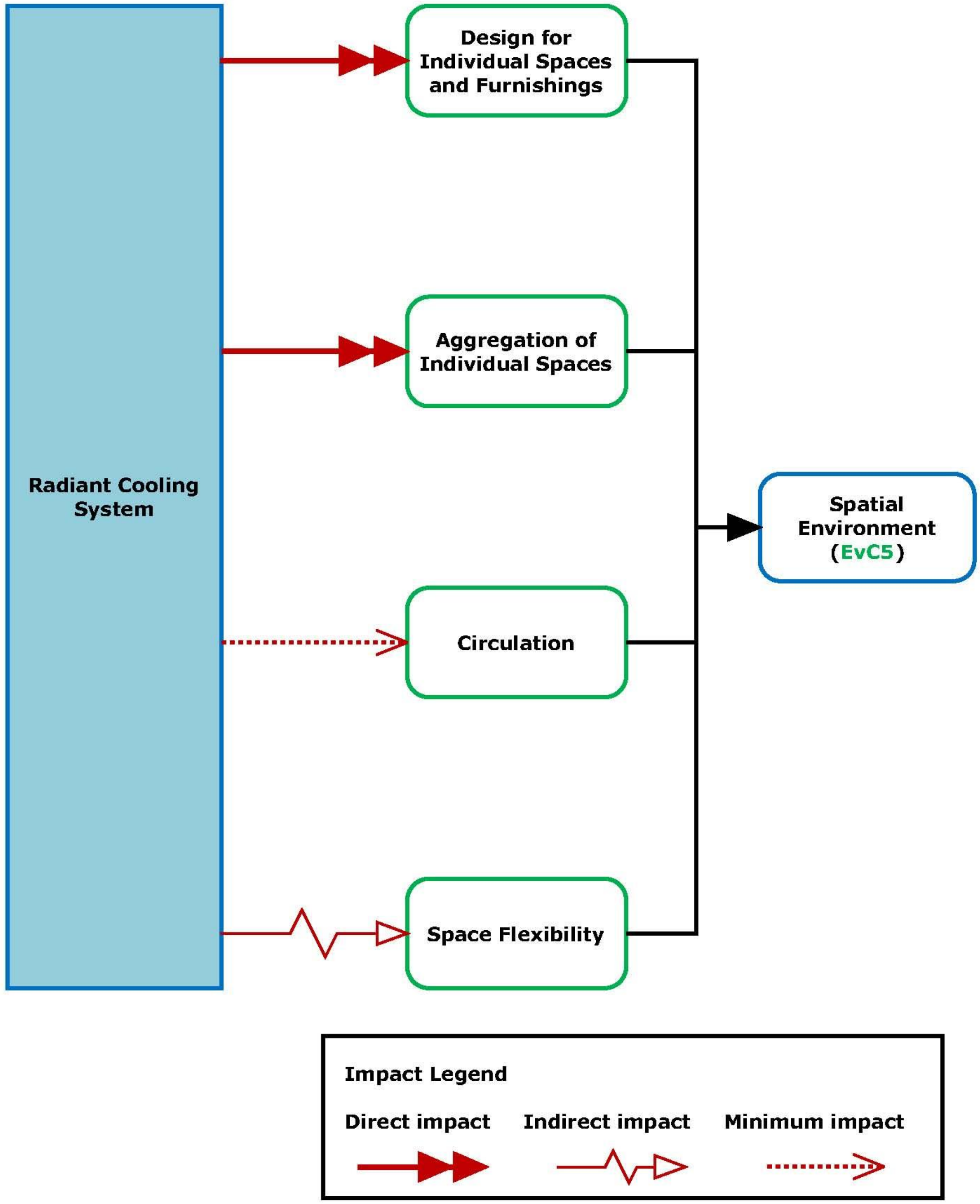


Figure 4.26. Spatial environment evaluative category (EvC5)

Discussion:

Figure 4.26 presents the possible impacts of installing a RC system on the spatial environment. These impacts are explained in the following:

a) Direct impact

i. *Design for individual spaces and furnishing*

In general, the RC system is recommended for spaces that need evenly distributed cooling loads. Crowded spaces may need special attention and possibly supplementary cooling sources. The ability to zone the RC system according to the space cooling loads gives it the needed flexibility.

Chilled slab systems: Chilled slab systems can be installed in spaces with relatively low cooling capacity and in spaces with high cooling capacity as long as the cooling loads are steady and do not fluctuate rapidly.

Furniture on the chilled slab with active floor sides will minimize the radiant heat exchange between the occupants and the cooled slab and thus minimize the cooling capacity of the system. In this case it is advisable to keep the floor uncovered as much as possible. If the thermally active sides are the ceiling then the system will not impact furniture distribution.

RCCP: RCCP can be installed in spaces with different cooling loads, either steady or dynamic. The system will not impact the furniture distribution. However, some vertical furniture such as bookshelves may interrupt the line of sight between the occupants and the cold surfaces.

ii. Aggregation of individual spaces

The case studies revealed that it is a common design strategy when implementing a RC system to group spaces according to their mechanical system. Typically, in projects where a RC system is used, spaces with conventional all-air HVAC systems are located in special zones or floors. This grouping makes the mechanical systems implementation more cost beneficial.

After assessing the spaces individually for whether a RC system could be implemented or not, spaces with and without RC systems are grouped together for easier system implementation.

b) Indirect impact

Space flexibility

Spaces with RC systems will have more flexibility for changing the space program when compared to conventional all-air HVAC systems if the cooling loads are similar. However, the only constraint in changing the space program would be the ventilation strategy and layout.

c) Minimum impact

RC systems will have minimum impact on the space circulation.

4.7 Critical Review and Feedback

4.7.1 Introduction

After mapping the framework variables and evaluative categories, they were presented to a group of stakeholders who have experience with RC systems design and implementation. The group included four architects with different levels of experience. These architects are part of the design team in an award winning architecture, interior design and planning firm that practices internationally from offices in the U.S. This firm has extensive experience with the design of urban mixed-use, multi-family residential, hotel, corporate office, higher education, laboratory, and transportation facilities.

The meeting took place in the firm office, where the researcher presented the framework for discussion and comments. The goal of the meeting was to answer the following questions:

a) Did the framework capture the RC system design and implementation processes?
b) What if anything is missing from the framework?
c) What could be done to improve the framework?
d) How useful is the framework?
e) What do you think of the level of detail presented in the framework?
f) What would be the needs for future work?

The researcher began by explaining to the design team the goal of the meeting which was to solicit their feedback and comments, and critique the work presented to them by answering the previously mentioned questions. These questions were explained and discussed with the design team before the presentation, and the team members were asked to interrupt whenever they had comments or questions. The researcher presented the framework starting from the motivations behind conducting this research through the conclusions.

4.7.2 Summary of the comments and feedback

The following summarizes the findings of the critical review and feedback meeting. The discussion point is mentioned first (indicated in italic), followed by the design team comments.

a) *This work is a step in the efforts to bridge the gap between the different disciplines involved in the building industry. This work attempts to explain a mechanical system from an architectural perspective.*

The design team supported this idea and emphasized the need of such research. They said such research would minimize communication between the different disciplines, as they do not have to explain the system for each other upfront its implementation, thus would improve the architectural design process while enhancing the integration possibilities.

b) *The need for this research comes from the recognition that RC systems are promising systems; when designed correctly, they would reduce energy consumption in the building, and enhance thermal comfort and IAQ when compared to conventional all-air systems.*

The design team supported these claims, and they indicated that some of their clients adopted the RC system because of its energy saving potential, and later the same clients expressed their interest in the system because of the enhanced thermal environment.

c) *The slow adoption of RC systems in the U.S. is due to the lack of education and availability of design support tools for architects and other participant parties.*

The design team agreed with this point, and they explained that other involved parties such as contractors, owners, and official personnel also need to be educated about RC systems, as their role is as important as the architect's and HVAC engineer's in the system design and implementation.

d) *The research objective is to identify the different variables, constraints, and the architectural consequences of the RC system implementation and map them in a decision-support system.*

The design team indicated that this is a very important step before making the decision to implement any system in the building, especially for a relatively new system such as RC. They explained that new systems are usually promoted without mentioning the whole picture such as issues with architectural interactions or what are the system capabilities and limitations. Such study is valuable to all involved parties for successful results. They added that the exogenous variables are very important to be identified and understood as they are hidden most of the time.

e) *The research methodology followed the grounded theory approach where the theory emerges at the end and was not hypothesized at the beginning.*

The design team supported such an approach for the study which attempted to capture the knowledge and re-present it in a systematic way. They supported the idea of having three different sources to strengthen each other and to include the human factor. Also, they explained that such methodology would increase the framework acceptance especially for people new to RC systems.

f) *The sources of relevant knowledge were organized into groups: endogenous and exogenous variables, and evaluative categories. For RC systems the endogenous variables include: the cooling capacity, the surface temperature, the control approach, and the physical properties of the system.*

The design team explained that they could not think of any other variables to be added to the list. However, they said that the most important variable among these is the RC system physical properties as it was explained in the discussion of RC system physical properties (EnV4). Architects are usually concerned about the system finish material, appearance, color, and dimensions as they will affect other design issues such as the acoustical and spatial environments.

g) *The RC systems' exogenous variables include: designer's and client's goals and preferences, building codes and standards, climate (outdoor environment), space function, space characteristics, construction system type, and the ventilation strategy.*

The design team explained that these variables are the most important variables to be identified before RC system implementation. They explained that understanding these variables is the key to a successful system implementation. The design team explained that they could not think of any other variables to be added to the list. They said that the envelope configuration is among the most important variables to be understood when considering the RC system implementation.

h) *The framework explains how the RC system will affect different aspects of the designed environment, namely the building performance mandates. Building performance mandates include the thermal environment, the IAQ, the acoustical environment, the visual environment, and the spatial environment.*

The design team indicated that these evaluative categories are relevant, and gave nothing to be added to the list when considering the implementation of RC systems. However, they indicated that it is obvious to think of thermal environments when implementing the RC system, but designers new to the system should recognize the other building mandates and how they may be affected.

i) *To make the final decision whether to implement a RC system or not, the framework guides its user through two major steps: first to understand how the endogenous and exogenous variables will affect the RC system design and implementation, then to understand how the RC system will impact the building performance mandates in the given space.*

The design team indicated that they follow the same concept when implementing RC systems and any other systems in the space. They indicated that having such systematic procedures as shown in the framework is important and helpful for successful implementation.

j) *The framework will be presented graphically to make it more accessible and easier to read.*

The design team agreed with the concept to deliver the research outcomes graphically. They indicated that people most of the time prefer easy and self-explanatory graphical language to understand new concepts and ideas, while having the ability to go into details when needed.

The design team indicated that assigning different decisions to different groups might be helpful especially when the framework is targeting different users.

k) *Different examples of the mapped variables were explained and presented, to show the logic and systematic organization of the mapping procedures.*

The design team indicated that the mapping diagrams are very clear and easy to read and understand. They indicated that the mapping diagrams are easy to follow and they give a complete picture of each variable. They indicated that some of the explained relations are new to them but make sense and give deeper insight.

l) *Different examples of the mapped evaluative categories was explained and presented.*

The design team indicated that they are easy to read, follow, and understand. They also indicated that the diagrams explain new relations that might be very useful in future cases. The design team did not suggest new ideas or relations to be added or explained.

m) *The suggested eleven-step design process for the RC system implementation as explained in section 5.2.2 was presented.*

The design team indicated that these steps are general and abstract but comprehensive enough to guide the architect. They indicated that they follow these steps, more or less, intentionally and unintentionally in each design process. However, they concluded that having a general design process for one system is more theoretical than practical, as every case has its own circumstances and priorities.

n) *After the presentation and discussion the design team had the following suggestions and comments:*

i. The process related to the decision of designing and implementing a RC system was fully captured and systematically presented. They did not think of additional variables and they did not feel that variables were missing.

ii. The framework is comprehensive and covers all that the architect needs to know when considering a RC system.

iii. The mapping procedures were easy to follow and understand.

iv. People new to the RC system would find the presented information to be too much and overwhelming, so there is a need to simplify the presented diagrams and figures.
v. People new to the RC system need guidelines and step-by-step procedures more than comprehensive and informative information.
vi. When presenting a new system, people need to know the benefits over existing systems, thus comparing the system with other conventional systems would be more beneficial to positively promote RC systems.
vii. In practice, the cost of the system and its energy consumption are very important variables; they should be included in the framework to give a full picture.

5 CONCLUOSION

5.1 Introduction

Creating a sense of place through a comfortable indoor condition is a goal of the architectural design process, where thermal comfort is an important component of this condition. Also, there is a movement among the architectural disciplines to move towards energy-efficient buildings while improving the indoor environmental quality. The RC system is a promising system which has the potential to meet these objectives. Many research findings support the claims that the thermal environment is improved and energy consumption is reduced with RC systems when compared to other cooling systems.

The adoptation of RC systems in the U.S. has been relatively slow when compared to the European building sectors. A main reason for this slow adoptation is the lack of educational and demonstrational tools for the design and application of RC systems from an architectural point of view. To address this issue this research provides a decision-support framework, mainly for architects and decision-makers in the building sector, to help them when considering the use of RC systems in new designs.

To be most cost beneficial, RC systems should be considered and integrated during the early stages of design, where issues associated with the system must be understood and properly applied by the design team. This research identified the relevant design issues, barriers and constraints, and the relevant performance mandates when implementing a RC system in a given space, then mapped them into a decision-support framework to assist architects in the design and integration of RC systems in the early stages of design. Through this decision-support framework the decision-maker will know a) whether the system is applicable for the space under investigation or not for a given building type, and b) what are the consequences of the system implementation in light of the performance of other building mandates.

5.2 Methodology

The grounded theory approach was used to capture and structure the knowledge related to the RC systems' design and implementation. The grounded theory is a systematic inductive theory generation methodology, where the research theory, in this case a decision-support framework, emerges at the end. The grounded theory approach allows using more than one tactic such as interviews and case studies to gather date, which was essential to capture the subjectivity of the architectural design process, when implementing the RC system.

The information needed to develop this framework was gathered from three different resources: systematic literature review, case studies, and interviews with RC system experts. This triangulation was done to enrich the captured information, to fill the gaps between each source, and as a way of validating the revealed findings. The captured knowledge was organized into three different groups; the framework inputs which contain the RC system endogenous and exogenous variables, the framework evaluative categories, and the framework assessment procedures. This categorization helps when mapping the different variables in a systematic way, where they were presented graphically to be accessible easily to the framework users. After mapping the variables, the proposed framework was presented to a group of professionals to solicit their comments and feedback.

5.3 Sources of Knowledge

Three different research methods were used to identify the relevant knowledge related to the design and implementation of RC systems from an architectural point of view. The first method was the systematic literature review; where scholarly works related to the RC systems were discussed and analyzed from an architectural point of view. The second method was the case studies; case studies were used as an instrument to give practical information for the design and implementation of the RC systems. The third method was the interviews; to capture the selection approach and subjectivity in the design process when using RC systems.

Based on the findings of the systematic literature review, the initial framework was built and mapped with all variables. The case study supported the findings revealed from the systematic literature review and there were no contradictions. These findings clarify some points and gave deeper inside into the process from a practical point of view. The interview findings supported those revealed from both the systematic literature review and the case studies. These findings helped clarify additional design decisions and gave a more complete picture of the situation. The interviews also helped define the interactions between the architectural and the engineering decisions when designing and implementing the RC system.

5.4 Mapping the Variables

Analyzing the different sources of relevant knowledge revealed many variables. The emerging variables have classified into three different groups: endogenous and exogenous variables, and the system evaluative categories. The endogenous and exogenous variables were mapped to help the framework user make an initial decision whether the RC system is applicable for the space under investigation and to understand the architectural consequences of the system implementation. The evaluative categories were mapped to help the user predict the performance of the building mandates when having the RC system in a given space. Based on the map these two sets of variables the decision-maker can decide to proceed with the RC system or to consider another system.

The endogenous variables are those which proceed from within the RC system and their values define the system. These variables can be altered by the framework user or they could be fixed. The RC system endogenous variables are the RC system cooling capacity, the RC system surface temperature, the RC system control sequencing, and the RC system physical properties.

The exogenous variables are those which originate from outside the RC system. These variables could be dependent and altered by the framework user, or could be independent and fixed. The values of these variables typically have direct and indirect effects on the configuration and performance of the RC system. The RC system exogenous variables include the designer's and client's goals and preferences, building codes and standards, climate, space function, space characteristics, construction system type, and the ventilation strategy.

The framework evaluative categories are the expected performance of the system with respect to the relevant building mandates when implementing the RC system in a given space. They are the thermal performance, the IAQ performance, the acoustical performance, the visual performance, and the spatial performance.

After identifying and categorizing the variables they were mapped to show the relations and explain their effects on the decision to implement the RC system. The influence diagram graphical language was used to present this mapping and to make the framework accessible for its users. While using the influence diagram, the framework variables were further categorized to make it easier to read. The variables were categorized into: the variables under investigation, variables controlled by the architects, variables controlled by the HVAC engineer, pre-determined variables, calculated variables, and variables left for future research. The influence diagram was divided vertically into a) boundary conditions, which contain the pre-determined variables, b) decisions, which contain the variables the decision-maker has to decide upon, and c) outcomes, which contain the variables that will be affected by the previous decisions.

5.5 RC system Implementation Process

By mapping the RC system variables, the designer has a decision analysis tool which provides insight about the RC system implementation process, objectives, and tradeoffs with other systems. The mapping of the variables provides the needed knowledge and information to take action and make decisions related to the RC system design and implementation process. The mapping of the variables clarified the architectural decisions for the RC system implementation and suggests a schematic and systematic design process for RC system design and implementation.

5.5.1 Architectural decisions for RC systems implementation

The mapping process of the endogenous and exogenous variables of the RC systems revealed some architectural decisions to be made for successful implementation of the system. The visibility of these decisions should be considered carefully by the design team before and while considering the decision to implement the system. However, while these decisions are mostly related to the thermal and IAQ environments of the space under investigation, other considerations related to the other building mandates are discussed in section 4.6.

5.5.1.1 RC system types

When choosing the RC system type for the space under investigation the designer must consider the following:

a) *The cooling capacity*

Different RC system types have different cooling capacities: the chilled slab system has a maximum cooling capacity up to 24 Btu/h•ft². In areas exposed to direct sunlight the cooling capacity could be increased up to 32 Btu/h•ft². Floor carpet can reduce the cooling capacity by 50%.

RCCP systems have a maximum cooling capacity of 30 Btu/h•ft² (Thornton et al. 2009)

b) *The ventilation system*

The RC system type can limit the options for the ventilation system. In general all RC systems types can be installed in naturally ventilated buildings.

i. *Chilled slab systems with active floor sides (chilled floor):* typically underfloor ventilation systems with raised floors are not used. A displacement ventilation systems may be used where air registers are above the floors.

ii. *Chilled slab system with active ceiling sides and RCCP systems:* mix ventilation systems (mounted in the ceiling) could be used, however displacement ventilation systems or underfloor ventilation systems are typically used with this system.

iii. *Chilled slab system with both sides active:* the ventilation air is supplied through the walls to keep the ceilings and floor uninterrupted and maximize the radiant heat exchange.

iv. *IAQ:* different combinations of RC system types and ventilation system types result in different IAQ environments. The most critical systems combination is the RCCP and displacement ventilation as discussed in section 3.1.2.5.1. However, it is recommended to run a numerical simulation for the space to predict IAQ.

c) Space geometry

i. There is no limitation on the maximum area the RC system can occupy. However, the cooled surface area, its surface temperature, and the distance between the cooled surface and the heat sources play important roles in defining the system cooling capacity.

ii. The ceiling height of the space may limit the RC system type selection. The experts explained that in high ceiling spaces, above 13 feet, RCCP systems and chilled slab systems with active ceiling sides are ineffective as their view factor becomes smaller which reduces the radiant heat exchange.

iii. If spaces are exposed to direct sunlight for relatively long periods of time, then chilled slab systems are preferred as they can directly remove the associated heat before affecting the thermal environment of the space.

d) Space function

i. Each space program suggests different occupant load profiles, this affects the RC system type selection. In spaces with dynamic cooling loads, such as classrooms or meeting halls, RCCP systems are recommended as they are quicker to respond to changing cooling loads when compared to chilled slab systems.

ii. It is important to understand the current and expected future function of the space. For example, if the space needs a raised floor to function then the chilled floor system is not preferred. If the floor is expected to support heavy machinery, then this requirement should be considered in the slab design if the chilled floor system is selected.

iii. It is common practice for architects to group spaces with similar cooling loads into a common zone or floor within the building. This will help when making the decision to use the appropriate systems and to provide an acceptable thermal environment.

e) Construction system

Typically chilled slab systems are integrated with concrete slab systems construction. If the building structural system does not support or include concrete slabs then implementing RCCP systems may be the only option.

5.5.1.2 Envelope configuration

The building envelope configuration is another architectural design factor when designing and implementing RC systems. The following must be considered by the designer:

a) Minimizing external heat gain and internal heat gains:

   i. RC systems have limited cooling capacity and thus space cooling loads have to be minimized. The designer can minimize the external heat loads through the envelope design and configuration. Solar heat gain through fenestration can be minimized using shading devices or by installing high performance glazing systems. Conduction heat gain through walls, roofs and fenestration could be minimized with enhanced insulation and by using reflective roof membranes.

   ii. Minimizing internal heat gain: designers can reduce the heat gain from the artificial lighting systems by using energy-efficient lighting, installing occupancy sensor control, harvesting daylight, etc.

b) Minimize infiltration

   RC systems only satisfy sensible cooling of the space, where latent loads are satisfied by additional systems. Infiltration is a major factor affecting the space latent cooling loads. High latent cooling loads increases the chances for condensation on the cooled surfaces of the RC system and limits the RC system cooling capacity.

c) Windows and glazed areas

   i. The glazed areas of the envelope must be designed and treated to prevent direct sunlight penetration, especially for spaces where people are typically seated, as it may cause local thermal discomfort by having radiant temperature asymmetry.

   ii. Direct sunlight in the space may raise the MRT temperature inside the space and adversely affect the thermal environment.

d) Ventilation strategy

   The envelope configuration will affect the selection for the ventilation strategy. Natural ventilation usually requires operable windows, and special envelope configurations to keep the sun’s heat out while permitting the air in or out. With mechanical ventilation systems, the envelope should minimize the infiltration and exfiltration rates to help the RC system meet the space loads.

5.5.2 Design process

ASHRAE handbook: HVAC Systems and Equipment 2008, Chapter 12 “Hydronic Heating and Cooling System Design” provides general guidelines for RC system design from an engineering point of view. Jeong and Mumma (2006) described eight steps for designing a Dedicated Outdoor Air System (DOAS) with RCCP systems. They also described the design process from an engineering point of view neglecting the role of architect in the implementation process.

This section provides a schematic and systematic design process for the design and implementation of the RC systems emphasizing the role of the architect in the implementation process which starts from the early stages of the building design.

Step one:

Establish the goal to produce a building with low energy consumption while enhancing the internal thermal environment. This target is set by the client or the by design team.

Step two:

Establish the RC system as an alternative mechanical cooling system with the potential to meet the goals in step one. However, it should be recognized that the RC system has limited cooling capacity. Therefore the next step in the design process is to minimize the space cooling loads, latent and sensible. There are many ways to reduce the space cooling loads through design.

Step three:

Determine the final building configuration that serves the client's goals, produces the best indoor environment, and consumes the least amount of energy. Computer energy simulation software could be used during this stage as an analysis tool. However, approaches to achieve the previously stated goals will differ from project to project.

Step four:

Understand the RC system abilities, advantages, and limitations. Understand the architectural and engineering decisions and consequences of the system design and implementation. This document explains and clarifies these topics and gives a full picture of the system implementation and design. Technical details can be obtained from other sources such as *ASHRAE handbook: HVAC Systems and Equipment - 2008.*

Step Five:

Determine the RC system type that best serves the targeted space. Refer to section 5.5.1.1 for recommendations for the RC system type selection.

Step six:

a) Calculations: this step is better described in engineering references such as *ASHRAE handbook: HVAC Systems and Equipment 2008* and other technical papers. However, this step may include the following a process as described by Jeong and Mumma (2006):

   i. Calculate the space (zone) peak cooling loads (latent and sensible).
   iii. Determine the desired space conditions i.e. room temperature, RH, operative temperature.
   iv. Calculate the required ventilation rate, and determine its desired conditions.
   v. Calculate the amount of cooling loads the ventilation system will need to meet.
   vi. Determine the sensible cooling load for the RC system.
   vii. Determine the RC system cooling capacity, and then determine the required area for the system.

Step seven:

Based on the previous step and on understanding the space function, determine spaces with dynamic cooling loads which require supplementary cooling systems to meet the cooling loads. Revise the RC system selection as performed in step five and determine the supplementary cooling system.

Step eight:

Evaluate the selected RC system performance in light of other building mandates as explained in section 4.6, and resolve any possible conflicts that may occur.

Step nine:

Determine the final configuration of the system and look for integration possibilities such as with the artificial lighting system, the ventilation system, and the fire suppression system.

Step ten:

Apply control systems to maintain the target room conditions as desired, and to run the RC system accordingly.

Step eleven:

Educate occupants about the system operation as well as other energy efficient systems in the building. This is an important step for the system performance and to avoid possible operation failure.

5.6 Future research

The outcomes of this research suggested several possibilities for future research and development:

a) Weaving the architectural and the engineering propositions of the RC system design and implementation into one framework. While this research focuses mainly on the architectural decisions related to the RC system implementation, the engineering decisions will specify the thermal performance of the system which is the main function of the RC system. Weaving the architectural and engineering decisions together into one framework will complete the picture and provide a new design tool.

   This research defined the architectural and engineering decisions that have to be made when designing and implementing RC systems. It also identified the relevant evaluative categories. This research discussed these variables separately to make the framework open for additional variables. The future work would connect all these variables together so the outcomes would establish well-defined design procedures the decision-maker has to make.

b) After weaving the architectural and engineering decisions related to the design and implementation of the RC system together, digitizing the framework will produce a practical tool for designers and decision-makers. For this process, the user will identify the project's pre-determined variables. Then the user will identify the expected performance according to several building mandates in the space under investigation. The variables identified through this framework can be changed by the user accordingly to determine the expected performance. The digital framework could be adapted to CAD and BIM design assistance tools to use the architectural decisions already made there. This adaptation will save time and money for the decision-maker while giving a full picture of the space's expected performance.

c) Include the cost and energy consumption of the RC system in the framework. The framework developed in this research is to be used during the preliminary stages of the architectural design process. In practice, after making the initial decision about the system implementation, the cost and the energy consumption of the system become the final sets of information. The RC system cost should include all related variables in addition to installation cost. Also, the radiant system will be used for heating and cooling purposes and this should be included in the energy consumption calculations.

d) While this framework discuss only one cooling strategy, RC systems, comparing the system to other cooling systems and strategies would help the decision-maker when choosing the best system for the space under investigation. This step could be achieved by analyzing different cooling systems following the same procedures performed in this research, and then compare the different architectural and engineering consequences of each system's implementation, including the cost and energy consumption. Then a decision-making system such as Choosing By Advantages (CBA) could be applied to choose the cooling system that would work the best for the space under investigation.

6 REFERENCES

Airfloor, Inc. 2009. *Airfloor Conditioning Systems*. Airfloor 2009 [cited May 2009]. Available from http://www.airfloor.com/.

Alamdari, F., D. J. G. Butler, P. F. Grigg, and M. R. Shaw. 1998. Chilled Ceilings and Displacement Ventilation. *Renewable Energy* 15 (1-4): 300-305.

Ardehali, Mortaza, Nirvan Panah, and Theodore Smith. 2004. Proof of Concept Modeling of Energy Transfer Mechanisms for Radiant Conditioning Panels. *Energy Conversion and Management* 45 (13-14): 2005-2017.

ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2009. *ASHRAE Handbook of Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

ASHRAE, American Society of Heating, Refrigerating and Air Conditioning Engineering. 2004. Thermal Environmental Conditions for Human Occupancy (ANSI/ASHRAE 55). Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineering Inc.

ASHRAE, American Society of Heating, Refrigerating and Air Conditioning Engineering. 2007. ASHRAE standard for Ventilation for Acceptable Indoor Air Quality (ANSI/ASHRAE 62.1). Atlanta: American Socitey of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

B. Berglund, B. Brunekreef, H. Knöppe, T. Lindvall, M. Maroni, L. Mølhave, and P. Skov. 1992. Effects of Indoor Air Pollution on Human Health. *Indoor Air* 2 (1): 2-25.

Beed, Terence W., and Robert J. Stimson. 1985. *Survey Interviewing : Theory and Techniques*. 1 ed. Sydney, Boston: HarperCollins Publishers Ltd.

Behne, Martin. 1999. Indoor Air Quality in Rooms with Cooled Ceilings: Mixing Ventilation or Rather Displacement Ventilation? *Energy and Buildings* 30 (2): 155-166.

Boubekri, Mohamed, Robert B. Hull, and Lester L. Boyer. 1991. Impact of Window Size and Sunlight Penetration on Office Workers' Mood and Satisfaction: A Novel Way of Assessing Sunlight. *Environment and Behavior* 23 (4): 474-493.

Brager, Gail S., and Richard J. de Dear. 1997. Thermal Adaptation in the Built Environment: A Literature Review. *Energy and Buildings* 27 (1): 83-96.

Brown, G. Z., and Mark DeKay. 2001. *Sun, Wind & Light : Architectural Design Strategies*. 2nd ed. New York: Wiley.

BuldingGreen.com. 2011. *William J. Clinton Presidential Center*. BuldingGreen.com 2007 [cited May 2011]. Available from http://www.buildinggreen.com.

Cilento, Karen. 2011. *Kripalu Center for Yoga & Health* (July 2010). Plataforma Networks 2010 [cited May 2011]. Available from http://www.archdaily.com/.

Clemen, Robert. 1996. *Making Hard Decisions: An Introduction to Decision Analysis*. 2nd ed. New York: Duxbury Press.

Colome, Steven, Robert J. McCunney, Jonathan M. Samet, and David Swankin. 1996. *Indoor Air Pollution: An Introduction for Health Professionals*. Washington, DC: US Consumer Product Safety Commission.

Conroy, Christopher L., and Stanley Mumma. 2001. Ceiling Radiant Cooling Panels as a Viable Distributed Parallel Sensible Cooling Technology Integrated with Dedicated Outdoor Air Systems. *ASHRAE Transactions* 107 (1): 578-588.

Costelloe, Ben, and Donal Finn. 2003. Indirect Evaporative Cooling Potential in Air-Water Systems in Temperate Climates. *Energy and Buildings* 35 (6): 573-591.

Creswell, John W. 2003. *Research Design :Qualitative, Quantitative, and Mixed Method Approaches*. 2nd ed. California: Sage Publications, Inc.

Dagostino, Frank R., and Joseph B. Wujek. 2004. *Mechanical and Electrical Systems in Construction and Architecture*. 4th ed. Prentice Hall.

Daniel Solomon Design Partners. 2011. *The David Brower Center*. Daniel Solomon Design Partners 2011 [cited May 2011]. Available from http://www.dsolomondesignpartners.com/.

Dassler, Friedrich H. 2011. *Activating the Four Season Landscape: The Annex at Kripalu Center for Yoga and Health*. xia-international-online, smart buildings – materials – technologies 2010 [cited May 2011]. Available from http://www.xia-international-online.com.

de Dear, Richard , and Gail Schiller Brager. 1998. Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions* 104 (1): 145-167.

Dieckmann, John, Kkurt W. Roth, and James. Brodrick. 2004. Radiant Ceiling Cooling. *ASHRAE Journal* 46 (6): 42-43.

Dietrich, Schmidt. 2009. Low Exergy Systems for High-Performance Buildings and Communities. *Energy and Buildings* 41 (3): 331-336.

DiNardi, Salvatore R. 2003. *The Occupational Environment: Its Evaluation and Control*. 2nd ed. Fairfax, Virginia: American Industrial Hygiene Association.

Douglas, James. 1994. Developments in Appraising the Total Performance of Buildings. *Structural Survey* 12 (6): 10-15.

Earth System Research Laboratory. 2010. *Annual Greenhouse Gas Index (AGGI)*. National Oceanic and Atmospheric Administration 2010 [cited March 2010]. Available from http://www.esrl.noaa.gov.

Egan, M. David. 1988. *Architectural Acoustics*. New York: McGraw-Hill.

Energy Efficiency Office of the Electrical and Mechanical Services Department. 2009. *Radiant Ceiling Cooling*. Hong Kong Energy Efficiency Net 2009 [cited January 2009]. Available from http://ee.emsd.gov.hk.

Energy Information Administration. 2010. Annual Energy Review 2008. U.S.A: Energy Information Administration.

Evans, Gary, and Rachel Stecker. 2004. Motivational Consequences of Environmental Stress. *Journal of Environmental Psychology* 24 (2): 143-165.

Faridah, A., A. Abdullah Sani, and R. Ismail. 2004. Bridging the Gap: Architecture and Structural Engineering. In *Conference On Engineering Education* Kuala Lumpur, Malyasia.

Feustel, Helmut E. 1999. A Special Issue Devoted to Hydraulic Radiant Cooling of Buildings - Instead of a Foreword. *Energy and Buildings* 30 (2): 117-120.

Feustel, Helmut E., and Corina Stetiu. 1995. Hydronic Radiant Cooling: Preliminary Assessment. *Energy and Buildings* 22 (3): 193-205.

Fisk, William J., and Arthur H. Rosenfeld. 1998. Potential Nationwide Improvements in Productivity and Health from Better Indoor Environments. Paper read at ACEEE Summer Study on Energy and Efficiency in Buildings, at Pacific Grove, California.

Flynn, John E., Jack A. Kremers, Arthur W. Segil, and Gary R. Steffy. 1992. *Architectural Interior Systems : Lighting, Acoustics, Air Conditioning*. 3rd ed. New York: Van Nostrand Reinhold.

Flyvbjerg, Bent. 2006. Five Misunderstandings About Case-Study Research. *Qualitative Inquiry* 12 (2): 219-245.

Foster, Bruce E. 1972. Performance Concept in Buildings, May, 1972, at Philadelphia, Pennsylvania.

Giovannini, Joseph. 2011. Housing Tower at Kripalu Center. *Architect*, January, 2011.

Glaser, Barney G., and Anselm L. Strauss. 2006. *The Discovery of Grounded Theory; Strategies for Qualitative Research*. 9th ed. New Brunswick, New Jersy: Aldine Transaction.

Glasser, David Evan. 2002. Smarterarchitecture. In *Smarterarchitecture*, edited by D. E. Glasser and S. Yavuz. Arkansas: Arkansas Department of Economic Development Energy Office.

Green Building Initiative. 2011. *William J. Clinton Presidential Center Case Study* (November 2006). Green Building Initiative 2011 [cited May 2011]. Available from http://www.thegbi.org.

Groat, Linda N., and David Wang. 2002. *Architectural Research Methods*. 2nd ed. New York: Jone Wiley and Sons.

Hao, Xiaoli, Guoqiang Zhang, Youming Chen, Shenghua Zou, and Demetrios J. Moschandreas. 2007. A Combined System of Chilled Ceiling, Displacement Ventilation and Desiccant Dehumidification. *Building and Environment* 42 (9): 3298-3308.

Harriman, Lewis G. 2002. *The Dehumidification Handbook* 2nd ed. Amesbury, USA: Munters Cargocaire

Harvard Business School. 2006. *Decision Making: 5 Steps To Better Results*, Harvard University: Harvard Business School Press.

Hayter, Sheila, Paul Torcellini, Richard Hayter, and Ron Judkoff. 2001. The Energy Design Process for Designing and Constructing High-Performance Buildings. Paper read at 7th REHVA World Congress and Clima 2000, at Milan, Italy.

Heerwagen, Judith. 2000. Green Buildings, Organizational Success and Occupant Productivity. *Building Research and Information* 28 (5-6): 353–367.

Henze, Gregor P., Clemens Felsmann, Doreen E. Kalz, and Sebastian Herkel. 2008. Primary Energy and Comfort Performance of Ventilation Assisted Thermo-Active Building Systems in Continental Climates. *Energy and Buildings* 40 (2): 99-111.

Heschong, Lisa, Roger Wright, and Stacia Okura. 1999. Daylighting Impacts on Human Performance in School. *Journal of the Illuminating Engineering Society* 31 (2): 101-114.

Hodder, Simon. G., Dennis. L. Loveday, Ken. C. Parsons, and AH Taki. 1998. Thermal Comfort in Chilled Ceiling and Displacement Ventilation Environments: Vertical Radiant Temperature Asymmetry Effects. *Energy and Buildings* 27 (2): 167-173.

Holsapple, Clyde W., and Andrew B. Whinston. 1996. *Decision Support Systems :A Knowledge-Based Approach*. 10th ed. Cambridge: West Group.

Imanari, Takehito, Toshiaki Omori, and Kazuaki Bogaki. 1999. Thermal Comfort and Energy Consumption of the Radiant Ceiling Panel System: Comparison with the Conventional All-Air System. *Energy and Buildings* 30 (2): 167-175.

Integral Group. 2011. *David Brower Center - Integral Group's 8th LEED Platinum Building*. CSRwire 2011 [cited May 2011]. Available from http://www.csrwire.com/about.

International Organization for Standardization. 2005. ISO 7730: Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria (ISO 7730). Switzerland: International Organization for Standardization.

International Organization for Standardization. 1984. Performance Standards in Buildings-Principles for their Preparation and Factors to be Considered (ISO 6241). Switzerland: International Organization for Standardization.

Jardine Engineering Corporation. 2007. The Radiant Floor Cooling System Project at the New Bangkok Airport Jardine Engineering Corporation (JEC).

Jensen, KL, Edward Arens, and Leah Zagreus. 2005. Acoustical Quality in Office Workstations, As Assessed by Occupant Surveys. *Indoor Air* 24: 2401-2405.

Jeong, Jae-Weon, and Stanley Mumma. 2003. Ceiling Radiant Cooling Panel Capacity Enhanced by Mixed Convection in Mechanically Ventilated Spaces. *Applied Thermal Engineering* 23 (18): 2293-2306.

Jeong, Jae-Weon, and Stanley Mumma. 2003. Impact of Mixed Convection on Ceiling Radiant Cooling Panel Capacity. *Hvac&R Research* 9 (3): 251-257.

Jeong, Jae-Weon, and Stanley Mumma. 2004. Simplified Cooling Capacity Estimation Model for Top Insulated Metal Ceiling Radiant Cooling Panels. *Applied Thermal Engineering* 24 (14-15): 2055-2072.

Jeong, Jae-Weon, and Stanley Mumma. 2006. Designing a Dedicated Outdoor Air System with Ceiling Radiant Cooling Panels. *ASHRAE Journal* 48 (10): 56-66.

Jeong, Jae-Weon, and Stanley Mumma. 2007. Practical Cooling Capacity Estimation Model for a Suspended Metal Ceiling Radiant Cooling Panel. *Building and Environment* 42 (9): 3176-3185.

Kanoglu, Mehmet, Ibrahim Dincer, and Yunus Cengel. 2009. Exergy for Better Environment and Sustainability. *Environment, Development and Sustainability* 11 (5): 971-988.

KaRo Systems. 2007. *Capillary Tubes*. KaRo Systems 2007 [cited November 2007]. Available from http://www.naturalcooling.com.

Keeney, Ralph L., and Howard Raiffa. 1993. *Decisions with Multiple Objectives*. Cambridge University Press.

Kempton, Willett, and Loren Lutzehiser. 1992. Introduction. *Energy and Buildings* 18 (3-4): 171-176.

Kennedy, Hugh. 1985. From Polis to Madina: Urban Change in Late Antique and Early Islamic Syria. *Past and Present* 106 (1): 3-27.

Kessling, Wolfgang, Stefan Holst, and Matthias Schuler. 2004. Innovative Design Concept for the New Bangkok International Airport, NBIA. In *Symposium on Improving Building Systems in Hot and Humid Climates*. Texas A&M University Energy Systems Laboratory.

Kibert, Charles J. 2008. *Sustainable Construction: Green Building Design and Delivery*. 2nd ed. Hoboken, New jersy: John Wiley & Sons.

Kilkis, Birol. 2005. A Road Map for Emerging Low-Exergy HVAC Systems. *International Journal of Exergy* 2 (4): 348-365.

Kitagawa, Koichi, Noriko Komoda, Hiroko Hayano, and Shin-ichi Tanabe. 1999. Effect of Humidity and Small Air Movement on Thermal Comfort Under a Radiant Cooling Ceiling by subjective Experiments. *Energy and Buildings* 30 (2): 185-193.

Lavan, David, and Don McLauchlan. 2008. Lakefront Library: Radiant Systems Meet Natural Ventilation. *Engineered Systems* 25 (12): 26-34.

Lawrence Berkeley National Laboratory. *Indoor Air Quality (IAQ) Scientific Findings Resource Bank*. Lawrence Berkeley National Laboratory 2008. Available from http://www.iaqscience.lbl.gov/.

Leaman, Adrian, and Bill Bordass. 2005. Productivity in Buildings: The 'Killer' Variables. *Building Research and Information : The International Journal of Research, Development and Demonstration* 27 (1): 4.

Loveday, Dennis. L., Ken. C. Parsons, AH Taki, and Simon. G. Hodder. 2002. Displacement Ventilation Environments with Chilled Ceilings: Thermal Comfort Design within the Context of the BS EN ISO7730 versus Adaptive Debate. *Energy and Buildings* 34 (6): 573-579.

Macaulay, David R. 2010. Bridge of Possibilities. *Eco-structure*.

Madison Gas and Electric. 2009. *Dedicated Outdoor Air Systems* Madison Gas and Electric 2009 [cited May 2009]. Available from http://www.mge.com.

McLauchlan, Donald, and David Lavan. 2010. Efficiency by the Book. *High Performning Buildings*.

Medina, Mario A., and Bryan Young. 2006. A Perspective on the Effect of Climate and Local Environmental Variables on the Performance of Attic Radiant Barriers in the United States. *Building and Environment* 41 (12): 1767-1778.

Meinhold, Bridgette. 2011. *The David Brower Center Becomes Berkeley's First LEED Platinum Building*. Inhabitat.com 2011 [cited May 2011]. Available from http://inhabitat.com.

Memon, Rizwan A., Surapong Chirarattananon, and Prapapong Vangtook. 2008. Thermal Comfort Assessment and Application of Radiant Cooling: A Case Study. *Building and Environment* 43 (7): 1185-1196.

Miazga, Mike. 2011. Green From The Ground Up. *PM Engineer*.

Miriel, Jacques, L. Serres, and A. Trombe. 2002. Radiant Ceiling Panel Heating-Cooling Systems: Experimental and Simulated Study of the Performances, Thermal Comfort and Energy Consumptions. *Applied Thermal Engineering* 22 (16): 1861-1873.

Moe, Kiel. 2010. *Thermally Active Surfaces in Architecture*. 1st ed. New York: Princeton Architectural Press.

Moore, Timothy. 2008. Simulation of Radiant Cooling Performance With Evaporative Cooling Sources. University of California, Berkeley: Center for the Built Environment.

Moore, Timothy, Fred Bauman, and Charlie Huizenga. 2006. Radiant Cooling Research Scoping Study. University of California, Berkeley: Center for the Built Environment (CBE).

moreAEdesign. 2011. *More About: William J. Clinton Presidential Center*. moreAEdesign 2010 [cited May 2011]. Available from http://moreaedesign.wordpress.com.

Mumma, Stanley. 2001. Ceiling Panel Cooling Systems. *ASHRAE Journal* 43 (11): 28-32.

Mumma, Stanley. 2001. Dedicated Outdoor Air in Parallel with Chilled Ceiling System. *Engineered Systems* 18 (11): 65-66.

Mumma, Stanley. 2002. Safety and Comfort Using DOAS: Radiant Cooling Panel Systems. *ASHRAE Journal* 44 (10): 2.

Mumma, Stanley A. 2008. *Dedicated Outdoor Air Systems*. Stanley A. Mumma 2001 [cited March 2008]. Available from http://doas-radiant.psu.edu/.

Murphy/Jahn Inc. 2011. *Suvarnabhumi Airport, the New Bangkok International Airport*. Murphy/Jahn Inc. 2007 [cited April 2011]. Available from http://www.murphyjahn.com.

Newyork-architects.com. 2011. *William J. Clinton Presidential Center*. newyork-architects.com 2011 [cited May 2011]. Available from http://www.newyork-architects.com.

Novoselac, Atila, and Jelena Srebric. 2002. A Critical Review on the Performance and Design of Combined Cooled Ceiling and Displacement Ventilation Systems. *Energy and Buildings* 34 (5): 497-509.

Okoli, Chitu, and Kira Schabram. 2010. A Guide to Conducting a Systematic Literature Review of Information Systems Research. *Sprouts Working Papers on Information Systems* 10 (no. 2010): 1-49.

Olesen, Bjarne W. 1997. Possibilities and Limitations of Radiant Floor Cooling. *ASHRAE Transactions* 103 (1): 42-48.

Olesen, Bjarne W. 2002. Radiant Floor Heating in Theory, and Practice. *ASHRAE Journal* 44 (7): 19-24.

Olesen, Bjarne W. 2004. International Standards for the Indoor Environment. *Indoor Air* 14 (Suppl. 7): 18-26.

Olesen, Bjarne W. 2008. Radiant Floor Cooling Systems. *ASHRAE Journal* 50 (9): 16-20.

Olesen, Bjarne W., Rosendahl J, Kalisperis L N, Summers L H, and M Steinman. 1989. Methods for Measuring and Evaluating the Thermal Radiation in a Room. *ASHRAE Transactions* 95 (1): 1028-1055.

Olivas, Rafael. 2009. *Decision Trees; A Primer for Decision-making Professionals* 2007 [cited September 2009]. Available from http://www.stylusandslate.com/decision_trees/.

Oppenheim, A. N. 1992. *Questionnaire Design, Interviewing, and Attitude Measurement*. 1st ed. USA and Canada: St. Martin's Press.

Pacific Northwest National Laboratory, and Oak Ridge National Laboratory. 2010. Climate Zone Map for the United States In *Building America Best Practice Series*: Unitad States Department of Energy.

Passchier-Vermeer, Willy, and Wim F. Passchier. 2000. Noise Exposure and Public Health. *Environmental Health Perspectives* 108 (3): 123-131.

Pesaran, Ahmad A. 1994. A Review of Desiccant Dehumidification Technology. Golden, Colorado: National Renewable Energy Laboratory.

Peter Rose and Partners. 2010. *Kripalu Housing*. Peter Rose and Partners 2009 [cited September 2010]. Available from http://www.roseandpartners.com/.

Petticrew, Mark, and Helen Roberts. 2006. *Systematic Reviews in the Social Sciences: A Practical Guide*. 1st ed. USA: Wiley-Blackwell.

Pomerantz, Gary. 2005. Consulting-Specifying Engineer. *Consulting-Specifying Engineer.* (June): 36-38.

Ramsey, JD, and M.Y. Beshir. 1997. *The Occupational Environment: Its Evaluation and Control*. Edited by S. R. DiNardi, *Thermal Standards and Measurement Techniques*: The Press (Christchurch, N.Z.).

Reffat, Rabee, and Edward Harkness. 2001. Environmental Comfort Criteria: Weighting and Integration. *Journal of Performance of Constructed Facilites* 15 (3): 104-109.

Roth, Kurt W., Detlef Westphalen, John Dieckmann, Sephir D. Hamilton, and William Goetzler. 2002. Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential. Cambridge, MA: U.S. Department of Commerce.

Rumsey, Peter, and John Weale. 2011. Green from the Ground Up. *High Performning Buildings*.

Rush, Richard D. 1986. *The Building Systems Integration Handbook.* 1st ed. New York: Wiley.

Seppänen, Olli and Wiiliam J. Fisk. 2002. Association of Ventilation System Type with SBS Symptoms in Office Workers. *Indoor Air* 12 (2): 98-112.

Seppanen, Olli, William J. Fisk, and QH Lei. 2006. Effect of Temperature on Task Performance in Office Environment. Berkeley, California: Lawrence Berkeley National Laboratory.

Simmonds, Peter, Isaac Chambers, Bungane Mehlomakulu, and Chris Simmonds. 2006. Applied Performance of Radiant Ceiling Panels for Cooling. *ASHRAE Transactions* 112 (1): 368-376.

Simmonds, Peter, Bungane Mehlomakulu, and Thilo Ebert. 2006. Radiant Cooled Floors - Operation and Control Dependant upon Solar Radiation. *ASHRAE Transactions* 112 (1): 358-367.

SmithGroup. 2008. *Chilled Beams* 2008 [cited April 2008]. Available from http://www.smithgroup.com.

Software, BizEE. 2011. *Weather Data for Energy Professionals*. BizEE Software 2011 [cited July 2011]. Available from http://www.degreedays.net/about.

Solomon, Susan, Dahe Qin, Martin Manning, Zhenlin Chen, Melinda Marquis, Kristen B. Averyt, Melinda Tignor, and Henry Miller. 2007. Climate Change 2007: The Physical Science Basis. In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University

Somcharoenwattana, Wantana, Christoph Menke, Darunporn Kamolpus, and Duŝan Gvozdenac. 2004. Contribution of Decentralized Energy System as Climate Change Mitigation Option – an Analysis of District Cooling System and Power Plant (DCAP) at Suvarnabhumi Airport, Thailand. Trier, Germany: University of Applied Sciences Trier, Department of Building Engineering Services.

Stake, Robert E. 1995. *The Art Of Case Study Research*. 1st ed. USA: Sage Publications, Inc.

Stasko, John. 2009. *Questionnaire Design*. Georgia Institute of Technology 1997 [cited October 2009]. Available from http://www.cc.gatech.edu/classes.

Stetiu, Corina. 1998. Radiant Cooling in US Office Buildings: Towards Eliminating the Perception of Climate-Imposed Barriers, University of California at Berkeley, California.

Straube, John F. 2002. Moisture in Buildings. *ASHRAE Journal* 44 (1): 15-19.

Suhr, Jim. 1999. *The Choosing By Advantages Decisionmaking System*: Greenwood Publishing Group.

The American Institute of Architects. 2011. *William J. Clinton Presidential Center*. The American Institute of Architects 2007 [cited May 2011]. Available from http://www.aiatopten.org.

The American Institute of Architects. 2010. *The Housing Tower*. The American Institute of Architects 2010 [cited May 2010]. Available from http://www.aia.org.

The Green Building Initiative. 2011. *The William J. Clinton Presidential Center from the ground up*. The Green Building Initiative 2008 [cited May 2011]. Available from http://www.thegbi.org.

Thornton, Brian A., Weimin Wang, Michael D. Lane, Michael I. Rosenberg, and Bing Liu. 2009. Technical Support Document: 50% Energy Savings Design Technology Packages for Medium Office Buildings.

Tian, Zhen, and James Love. 2006. Radiant Slab Cooling: A Field Study of Occupant Thermal Comfort. In *SimBuild 2006*. Massachusetts Institute of Technology, Cambridge, MA: International Building Performance Simulation Association

Tian, Zhen, and James Love. 2009. Energy Performance Optimization of Radiant Slab Cooling Using Building Simulation and Field Measurements. *Energy and Buildings* 41 (3): 320-330.

U.S. Department of Energy. 2011. *William J. Clinton Presidential Center*. U.S. Department of Energy 2007 [cited May 2011]. Available from http://eere.buildinggreen.com.

U.S. Department of Energy. 2009. *U.S. Primary Energy Consumption by Source and Sector: 2008*. Energy Information Administration 20092009]. Available from http://www.eia.doe.gov.

Uponor. 2009. *Radiant Cooling Systems* 20092009]. Available from http://www.uponor-usa.com.

Vangtook, Prapapong, and Surapong Chirarattananon. 2006. An Experimental Investigation of Application of Radiant Cooling in Hot Humid Climate. *Energy and Buildings* 38 (4): 273-285.

Walsh, Paul. 2000. Targets and How to Assess Performance Against Them. *Benchmarking: An International Journal* 7 (3): 17.

Watson, Richard D., and Kirby S. Chapman. 2002. *Radiant Heating and Cooling Handbook*. New York: McGraw-Hill.

Whole Building Design Guide (WCDG). 2008. *Productive* 2008 [cited May 2008]. Available from http://www.wbdg.org/design/productive.php.

Wong, Nyuk Hien, and Wy Leng Seow Jan. 2003. Total Building Performance Evaluation of Academic Institution in Singapore. *Building and Environment* 38 (1): 161-176.

World Climate. 2011. *Average Weather Data*. World Climate 2007 [cited July 2011]. Available from http://www.climate-charts.com.

Yao, Runming, Baizhan Li, and Jing Liu. 2009. A Theoretical Adaptive Model of Thermal Comfort - Adaptive Predicted Mean Vote (aPMV). *Building and Environment* 44 (10): 2089-2096.

Zhisheng, Li, Li Dongmei, Mei Sheng, Zhang Guoqiang, and Liu Jianlong. 2007. Noise Impact and Improvement on Indoors Acoustic Comfort for the Building Adjacent to Heavy Traffic Road. *Chinese Journal of Population Resources and Environment* 5 (1).

Zmeureanu, R., and J. Brau. 2007. Hydronic Radiant Floor for Heating and Cooling Coupled with an Underground Heat Exchanger: Modeling Approach and Results. *Building Simulation 2007* 1 (3): 315-320.

7 APPENDIXES

7.1 Appendix A: Interview Questions

7.1.1 Group no. 1: Introductory questions

To establish a background about the respondent, the role he/she played in implementing the RC system, the RC system type he/she used, and the system's endogenous variables.

a) In general, what is your experience with radiant systems?
b) What is the nature of your experience with RC systems?
c) How many projects using RC systems have you been involved with?
    i. Can you explain the building type of these projects?
    ii. How does the building type influence the decision to use a RC system?
    iii. What types of RC systems do you have experience with? (ceiling systems, floor systems)
    iv. How does the building type influence the selection of one RC system type over another?
d) What factors lead to RC systems being initially considered?
    i. What were the differences in characteristics between the RC system and other systems that led you to consider RC?
e) Focusing only on the RC system, what makes a RC system differ from one to another?
    i. Does the RC system type influence the decision-making process? If so, how?
    ii. The following variables could be described as RC system endogenous variables: System cooling capacity, system surface temperature, system control, and system physical properties (such as dimensions of the RC system, finishing color of the cooled surfaces, locations and finish materials of the cooled surfaces).
        i. Would you like to add more variables?
        ii. Which one of these concerns you the most? Why?
        iii. What are the variables affecting the RC system cooling capacity?

iv. What are the variables affecting the system radiant temperature limits?
v. How may the RC system control affect the implementation decision?
vi. How may the system physical properties affect the implementation decision?

f) In general, what are the common barriers and constraints to implementing RC systems?
   i. How do you decide on if the barriers/constraints can be overcome and to continue with the RC system?
   ii. How do you address them?

7.1.2 Group no. 2: Design process

Identify the factors affecting the design process, exogenous variables, endogenous variables, and the limitations/constraints the designer may face.

a) Could you please describe briefly the process you go through when implementing a RC system in your project?
   i. How do you decide on whether to consider a RC system?
   ii. How do you decide the type of the RC system?
b) Once the decision is made to consider a RC system, in the early stages of the design, what are the factors you must be considered? For example is the climate a factor in deciding to implement a RC system? What other factors must be considered?
   i. Do these factors vary among projects, locations… and if so, how?
   ii. How do you address these factors?
   iii. For each of these factors, how do you evaluate performance?
      a. What tools do you use to evaluate performance?
      b. What is your level of confidence in these assessment procedures and tools?
   iv. The following variables could be described as RC system exogenous variables: designer's and client's goals and preferences, building codes and standards such as ASHRAE 55 and ASHRAE 621 and ASHRAE 90.1, climate (outdoor environment), space function, space characteristics, construction system type, additional system in the space, and the ventilation strategy.
      a. Would you like to add or omit any to this list?

b. Which of these variables are relevant when deciding to implement a RC system?

v. How do you see codes and standards govern the use and implementation of RC systems?

a. Do these codes limit the implementation process? If yes, can you name the code and explain how it limits the implementing process?

vi. How does climate affect the use of RC systems?

a. What concern you the most about the climate variables?

b. How do you deal with it?

vii. Space function affects the cooling loads, how do you deal with this?

a. Each space has its own characteristics such as geometry, window placement and finish material: how do these characteristics affect the decision to use a RC system?

b. How does the space height affect the decision to use a RC system?

c. How does the glazing area affect the decision to use a RC system?

viii. How does the construction system type affect the decision to implement a RC system in the space/building?

ix. How does the use of other systems inside the space affect the use and implementation of the RC system?

x. When using a RC system you have to make a decision about the ventilation strategy you will implement: how is this decision made?

a. How are these two systems related or affecting each other?

7.1.3 Group no. 3: Relationships with thermal comfort and IAQ

To study the direct relationship between the RC systems and thermal comfort and IAQ. To extract rules of thumb, recommendations, and solutions.

a) In general, when you are designing a space, what you are trying to achieve in that space? What kind of environment you are trying to create?

i. How do you evaluate these achievements?

ii. How do you evaluate the space's environment?

b) Richard Rush mentioned in his book six interior building performance mandates: Thermal performance, IAQ performance, Acoustical performance, Visual performance, and spatial performance,

i. Would you like to add any other mandates?

ii. When installing a RC system in the building, which of these performance mandates are you trying to address?

c) How will thermal performance affect the decisions to implement a RC system?

d) How will implementing a RC system in the space affect thermal performance?

i. Which of the following variables of thermal comfort will be affected: Operative temperature (which is the combination of mean radiant temperature and air temperature), Relative humidity, air speed, temperature variation with time?

ii. What are the concerns for thermal comfort when implementing a RC system?

iii. Will installing a RC system cause any kind of local thermal discomfort?

a. ASHRAE categorized local thermal discomfort to radiant asymmetry, draft, vertical air temperature differences, and floor surface temperature, which of these will be affected?

xi. How do you evaluate and decide on issues associated with the RC system?

c) How will IAQ performance affect the decisions to implement a RC system?

d) How will implementing a RC system in the space affect the IAQ performance?

7.1.4 Group no. 4: Relationships with other Building Performance Mandates (BPMs)

To study the relationship between the RC system and the other BPM. To extract rules of thumb, recommendations, and solutions.

a) Do you think installing a RC system in the space will affect the other building performance mandates? Which ones specifically?

b) How will acoustical performance affect the decisions to implement a RC system?

i. How will implementing a RC system in the space affect its acoustical performance?

e) How will visual performance affect the decisions to implement a RC system?

i. How will implementing a RC system in the space affect its visual performance?

f) How will thermal performance affect the decisions to implement a RC system?

   i. How will implementing a RC system in the space affect its spatial performance?

7.1.5 Group no. 5: Conclusion

a) Based on your design experience, do you have any recommendations for architects when implementing a RC system?

b) Would you like to add any additional information, comments, or clarification on any of the previous questions?

c) Are you willing to see the final product of this research, “the decision support framework”, and comment on it?