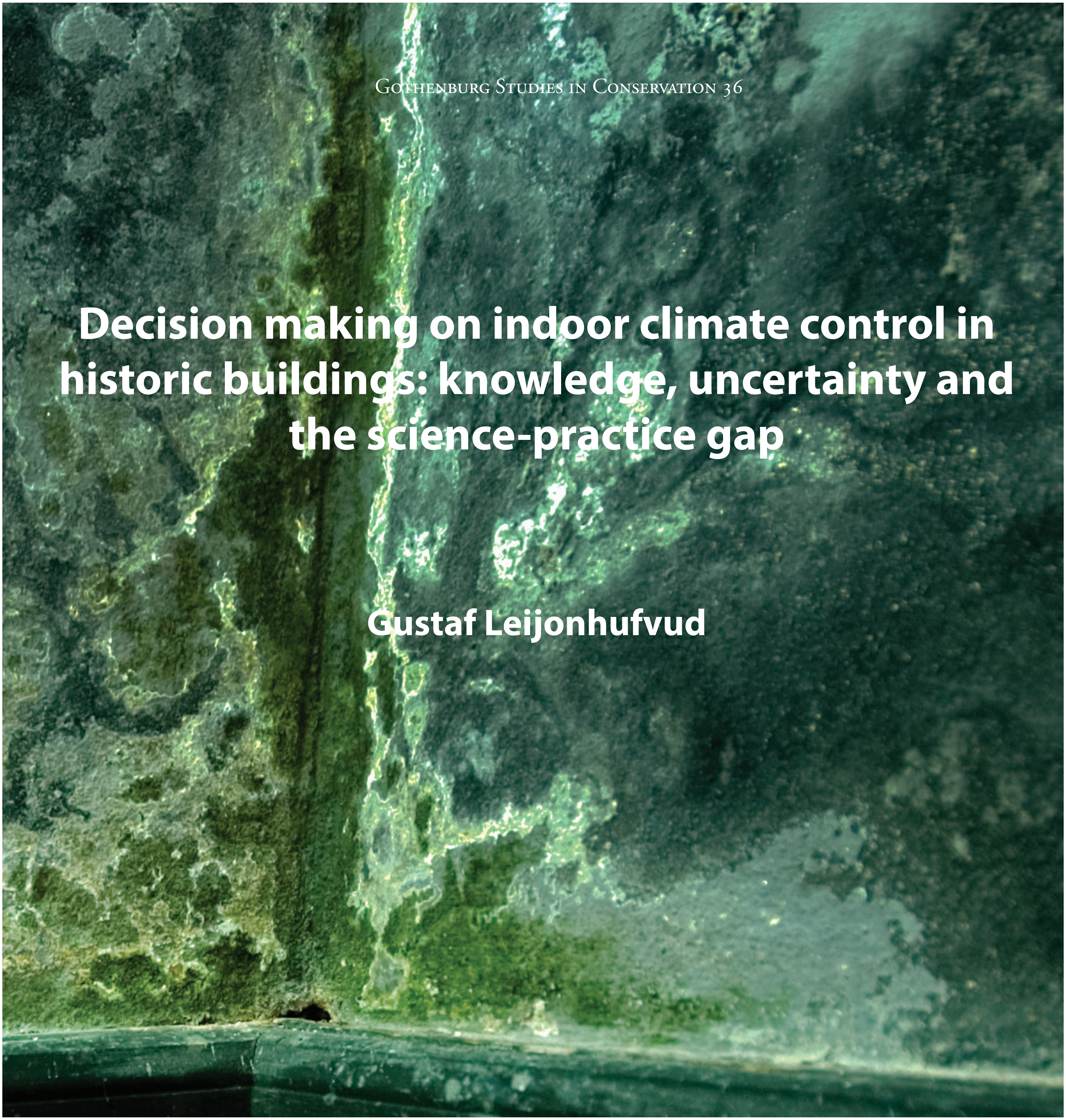
Decision making on indoor climate control in historic buildings: knowledge, uncertainty and the science-practice gap



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Decision making on indoor climate control in historic buildings: knowledge, uncertainty and the science-practice gap

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Cover: Algae growing on interior plaster in the manor house at Klints, Othem, Gotland. Photo by the author.

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Abstract

Balancing use, preservation and energy use is a fundamental challenge for the whole heritage field. This is put to the point in designing and operating systems for indoor climate control in historic buildings, where competing objectives such as preservation, comfort, accessibility, energy use and cost have to be negotiated in the individual case.

The overarching aim of this thesis is to explore the gap between research and practice regarding energy efficient indoor climate control in historic buildings. The thesis deals with historic buildings where both the building fabric and the movable collection are vulnerable and where the management of the building is more or less professionalized. Examples of such buildings are palaces, churches and historic house museums, ranging from the large and complex to the small and simple. A key to a more sustainable management of these buildings is to understand how scientific knowledge related to indoor climate control can become usable for the professional practitioner.

The thesis comprises six published papers introduced by a thesis essay. The papers reflect a progression both in terms of the research questions and the methodology. The first three papers outline the background needed for a technical understanding of the involved matters through an identification of key knowledge gaps. The three remaining papers use qualitative case studies to understand the nature of the gap between science and practice by paying more attention to the social aspects of decisions related to indoor climate control.

Generally, the results of the thesis contribute to an expanded problem definition and to a better understanding of the gap between research and practice regarding energy efficient indoor climate control in historic buildings. It is shown how the specific social and material context is crucial for enabling or limiting a transition toward more sustainable ways of controlling the indoor climate. Furthermore it is discussed how uncertainty can be managed and communicated to support decisions, and suggestions are given for how decision processes regarding indoor climate control can be supported with improved standards to facilitate a more sustainable management. A conclusion for further research is that scientific knowledge alone will not be able to guide the transition to a sustainable, low carbon future; technical research has to be complemented with reflexive research approaches that explore the actual practices of heritage management.

List of Papers

The present doctoral thesis is based on the following six papers, which will be referred to in the text by their Roman numerals.

I. Leijonhufvud, Gustaf and Charlotta Bylund-Melin. 2009. ”Preventive conservation climate in historic buildings – some gaps in the knowledge”. This paper has been translated from Swedish and was originally published in the Scandinavian peer-reviewed journal *Meddelser om konservering* no 1 2009, s. 22-30 with the title “Bevarandeklimat i historiska byggnader-Några kunskapsluckor.”

II. Leijonhufvud, Gustaf, Erik Kjellström, Tor Broström, Jonathan Ashley-Smith, and Dario Camuffo. 2013. “*Uncertainties in damage assessments of future indoor climates.”* In Climate for collections: Standards and uncertainties. Edited by Jonathan Ashley-Smith, Andreas Burmester, and Melanie Eibl, 405–18. London: Archetype Publications.

III. Broström, Tor, and Gustaf Leijonhufvud. 2010. “*The indoor climate in Skokloster Castle*.” In Historical buildings as museums: Systems for climate control and heritage preservation. Edited by Davide Del Curto, 84–93. Firenze: Nardini Editore.

IV. Leijonhufvud, Gustaf, and Annette Henning. 2014. "Rethinking indoor climate control in historic buildings: The importance of negotiated priorities and discursive hegemony at a Swedish museum." *Energy Research & Social Science* 4 (0): 117-23. doi: 10.1016/j.erss.2014.10.005.

V. Leijonhufvud, Gustaf. 2016. "Making sense of climate risk information: the case of future indoor climate risks in Swedish churches." *Climate Risk Management*. Available online 4 June 2016 doi:10.1016/j.crm.2016.05.003.

VI. Leijonhufvud, Gustaf, and Tor Broström. *"Standardizing the indoor climate in Swedish churches: opportunities, challenges and ways forward."* Manuscript. A shorter version of the manuscript has been accepted for publication in the proceedings of the 2nd International Conference on Energy Efficiency and Comfort of Historic Buildings, Brussels 2016.

My contribution to the co-authored papers:

Paper I. I am one of two first authors of this paper.

Paper II. I am the first author of this paper. Erik Kjellström wrote the section about uncertainties in the outdoor climate.

Paper III. I am one of two first authors of this paper. I and Tor Broström jointly conducted the empirical study and wrote the paper together.

Paper IV. I am the first author of this paper. I conducted the empirical study for this paper and wrote a draft version. I and Annette Henning jointly revised the whole paper.

Paper VI. I am the first author of this paper. I conducted the empirical study and wrote a draft version. I and Tor Broström jointly revised the whole paper.

Contents

1. Foreword

A challenging and rewarding journey has come to an end. In 2006, I finished the bachelor programme in building conservation at what was then Gotland University. The directive on energy performance in buildings, issued by the European Union, was at that time on its way to be implemented in Sweden. I got the opportunity to study how energy certificates could be applied in historic buildings in Sweden in my bachelor thesis. I had for some time been interested in how the management of cultural heritage could become more sustainable, and the implementation of the directive was an interesting and urgent topic relating to this question. The work with the thesis was stimulating and sparked a desire to understand more about the relationship between science, policy and practice in the interface between sustainability and conservation. A few years later I got the opportunity to dig deeper into these issues as a doctoral student in the *Spara och Bevara* research programme, this time with a focus on the indoor climate in historic buildings. Like all adventures, it has been far from a straight journey. Still, I have never hesitated about the importance of my subject, and today, after having ditched a few dead ends and connected some of the loose ends, I feel rewarded by the experience.

Energy efficiency in historic buildings had when I started my doctoral work been a neglected field in Sweden for many years. Mainly thanks to the Swedish Energy Agency, it is today an established interdisciplinary field of study with a strong and networking researcher and stakeholder community spread out over the country. It has been exciting to be a part of this development, and encouraging to see the results.

Acknowledgments

This thesis would not have existed without the support from my main supervisor Tor Broström, who always have had the time to give support and valuable feedback. I have been inspired by your ability of strategic and independent thinking, and encouraged by your trust in my own ability at times when I have been in doubt. I would also like to thank my supervisor Jonny Bjurman for helpful advice, and my examiner Ola Wetterberg for valuable support throughout the doctoral programme.

I am indebted to my co-authors for their valuable contributions. Thanks to Charlotta Bylund-Melin for fruitful collaboration with paper I and for good company during the whole doctoral programme. I am grateful over the opportunity to collaborate with Jonathan Ashley-Smith, Dario Camuffo and Erik Kjellström on Paper II, which was written in connection with the project Climate for Culture. I am also grateful for the constructive dialogue and encouragement from Annette Henning, and I am happy to have had the opportunity to collaborate with you in the writing of paper IV.

I would like to give a special thank to Mattias Légner for always insightful comments, which significantly have improved my texts. Many thanks also to Jan Holmberg, Jan Rosvall, Jonathan Ashley-Smith and Derek Worthing for inspiration and useful comments.

My colleagues at the Department of Conservation at the University of Gothenburg and at Campus Gotland, Uppsala University have made my workdays stimulating and fun. Special thanks to the ones in Visby that have been involved in research about energy efficiency in historic buildings, whom all have contributed to my thesis in one way or another: Fredrik Berg, Maria Brunskog, Susanna Carlsten, Anna Donarelli, Petra Eriksson, Paul Klenz Larsen and Magnus Wessberg,

Last, but not least, I would like to thank my precious girls, Harriet, Greta and Lou, and my parents, Gunilla and Olof, for their genuine support and for their patience at times when I had my head in the clouds.

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2. Introduction

Prologue: The King's hall, Skokloster castle, 7-8 November 2011.

A group of conservators, conservation scientists and curators have gathered around the glass chandelier hanging from the ceiling in the King's hall of Skokloster castle, a baroque palace close to Stockholm. The chandelier, presumably the oldest glass chandelier in the world, was produced by Melchior Jung's glassworks in 1670-71 and has been hanging in the King's chamber since 1672.[1] *Unfortunately, it is now severely deteriorated due to a fault in the chemical composition of the original glass formula. Salts in the glass hydrate when exposed for water molecules and leach out of the glass. The process is referred to as glass disease or weeping glass.*

The condition of the chandelier has been known for a long time, but no interventions, at least not in recent times, have been made to slow down the deterioration. The Swedish state took charge of the palace in 1968 after a long time of private ownership. The subsequent restoration was led by the architect Ove Hidemark, who considered the building a well-functioning, organic whole. Traditional techniques and materials were used to an extent which was unusual of the time. The management of the palace has since then been characterized by a policy to change as little as possible and repair only when necessary (Statens fastighetsverk 2005).

The group of professionals are in the King's hall to discuss the preservation of the chandelier, and to come up with possible interventions (Hallström 2011). There is little uncertainty regarding what kind of action that is needed to halt the on-going deterioration: A reduction of the ambient relative humidity to a low and stable level will effectively inhibit the process.

There is no active climate control in the room and the whole castle has been effectively unheated for centuries. The level of relative humidity is very high during winter and moderate during summer, conditions which are clearly unfavourable for the chandelier.

Various alternatives are discussed during the workshop. Could the chandelier be moved to a safer storage, where the environment can be controlled, and a replica be made to hang in its place? Unfortunately, the chandelier is now considered so fragile that the risks caused by moving it outweigh the benefit. Is there a possibility to actively control the indoor climate in the room? To reduce the relative humidity to a low level would risk the mechanical stability of other artefacts in the room, in addition to the negative effect of the technical installations needed for dehumidification or heating. Would it be possible to put a showcase around the chandelier, or to create a stream of dry air around it? Such options are out ruled because of the negative aesthetic influence in combination with being impractical. In the end, no option seems attractive, and the ambitious workshop ends without a conclusive recommendation. Some time afterwards it is decided that no intervention will be made, and the chandelier is still hanging in the room, slowly deteriorating.

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1. http://skoklostersslott.se/sv/den-sjuka-ljuskronan, accessed 2016-07-05.

The short episode above shows how decisions concerning the indoor climate in historic buildings are not only about solving technical problems; science alone cannot guide decisions. In contrast to most other cases, there was in this particular case certain and unambiguous knowledge available about the causal relationship between the deterioration process and the indoor climate. Still, decisions revolved around balancing different objectives, and value judgments turned out to be decisive. Previous policies, decisions and actions regarding the management of the palace turned out to have a dual impact: they had affected the physical state of the chandelier, but they also served as a discursive point of departure for the discussions at the workshop. The participants did not come to a tabula rasa.

The overarching aim of this thesis is to explore the gap between research and practice regarding energy efficient indoor climate control in historic buildings. I examine how managers of cultural collections and historic buildings make sense of the continuously improved scientific knowledge base and the possibilities and obstacles to use it when making decisions about indoor climate control. In their review of a "climate information usability gap", Lemos *et al.* (2012, p. 1) make a distinction between "useful" and "usable" information. They show that while researchers often are engaged in projects that aim to produce knowledge that is useful for a wide group of practitioners, it is common that the produced knowledge for various reasons remain ignored or unused, according to their analysis mainly due to a lack of alignment with the specific contexts and decision processes of actual practice. Hence, potentially "useful" information is often not considered "usable" by practitioners. Using the same distinction as theirs, I try to understand how useful scientific knowledge related to indoor climate control in historic buildings can become usable for the professional practitioner.

Balancing preservation, use and energy efficiency is a pressing issue for the whole heritage field (Barthel-Bouchier 2013). The case of the chandelier at Skokloster castle, albeit its brief description, illustrates how the indoor climate in a historic building is at the core of this issue, taking the role as both the problem and the solution. Indoor climate control is a crucial tool to improve preservation, use and energy efficiency, but there is not a priori answer to how these competing objectives should be balanced in the individual case. Hence, the fundamental challenge for the decision-making on indoor climate control in Skokloster castle, as well as in other historic buildings, is about negotiating different, and often conflicting, objectives.

Throughout the thesis the term "historic building" refers to a building which in itself has cultural heritage values and houses artefacts that are vulnerable to the indoor climate. It can be the building fabric itself, movable objects housed in the building, or both. The emphasis is on historic buildings where both the building fabric and the movable collection are vulnerable and where the management of the building is more or less professionalized. Examples of such buildings are palaces, churches and historic house museums, ranging from the large and complex to the small and simple.

The thesis is written in the light of that radical cuts in greenhouse gas emissions during the first half of the 21st century are necessary to avoid dangerous climate change, and that these cuts might have far-reaching consequences for how energy is produced and used. In the Paris agreement from 2015 it is stated that the increase of the global average temperature should be limited to well below 2 degrees above pre-industrial levels (United Nations / Framework Convention on Climate Change 2015). While rapid reductions are inscribed in the Paris agreement, it has been criticized for relying too much on future technological development than on the early and deep reductions suggested by climate scientists (Anderson 2015b).

In the EU and Sweden there are discrepancies between the long-term ambitions and the more short-term binding targets. The long term objective for greenhouse gas reduction in the EU is 80-95 % by year 2050, compared to 1990 levels (SOU 2016:47). In Sweden, a recent official report of the Swedish Government following on the Paris agreement suggests that Sweden should have zero net greenhouse gas emissions by 2045 (SOU 2016:47). The binding targets are less progressive: the EU has agreed on a binding target of 40% reduction of emissions by 2030 compared to 1990 (European Council 2014). The Swedish Government has agreed on reducing emissions by 40 % until 2020, compared to 1990 levels (SOU 2016:47). Despite the political visions represented by long-term reduction targets, it is a fact that the rate of decarbonisation in the global economy has been far below what is needed for avoiding dangerous climate change (Anderson and Bows 2008, Anderson 2015a). As an example, there has been little reduction of overall primary energy consumption and carbon emissions in the European building stock since 1975 (Kohler and Hassler 2012). Sweden is an exception and has seen a reduction of greenhouse gas emissions in buildings of 86 % compared to 1990 (SOU 2016:47). This reduction is primarily associated with a change to renewable energy sources (SOU 2016:47).

Transformation of the building stock is often considered as one of the most important and cost-efficient measures in decarbonization scenarios (Levine *et al.* 2007). On the global scale there is an urgent need to reduce greenhouse gas emissions associated with buildings (IPCC 2014). The technologies delivering indoor climate control have a relatively long life span, and decisions made today about indoor climate control will therefore have long-lasting effect not only on the conservation of artefacts, but also on energy use and greenhouse gas emissions. In general, there are significant lock-in risks associated with the long lifespans of buildings, hence action taken now will determine energy use and emissions for decades ahead and limit the opportunities for further change (IPCC 2014).

Even though historic buildings housing cultural collections make up a small part of the whole building stock and therefore have little impact on global greenhouse gas emissions, their long-term survival will be dependent on successful adaptation to a low carbon economy. The bar for what is considered an acceptable level of energy efficiency will therefore continue to rise for all types of buildings, also historic buildings. Despite a lack of legal requirements on energy efficiency in historic buildings in Sweden, there is substantial external as well as internal pressure on the owners and managers of historic buildings to reduce energy use and lower greenhouse gas emissions.

There is a raising awareness, both among policy-makers and practitioners, about the need for climate change mitigation within the cultural heritage sector (Silva and Henderson 2011, Barthel-Bouchier 2013, Staniforth 2014). This awareness is a part of a broader discourse within the sector about the contribution of cultural heritage to sustainability, in which energy issues play an important part. A recent review by Avrami (2016) focused on tensions around goals and rationales found in the literature on the intersection between sustainability and preservation. The review concluded that the evidence needed to demonstrate preservation's contributions to sustainability is lacking, despite a claim of the opposite evident in a recurring mantra from preservation advocates about the inherent sustainability of preservation.

In parallel to the emerging preservation-sustainability discourse there exist more tangible and concrete concerns about the impact of climate change to cultural heritage. In addition to external impacts to the historic fabric (e.g. Sabbioni *et al.* 2010), climate change will also influence the microclimate inside buildings (e.g. Lankester and Brimblecombe 2012, Kilian *et al.* 2013). As an example, climate change will increase the risk for mould growth in unheated historic buildings in northern Europe (Leissner *et al.* 2015). Unheated historic buildings which have had none or manageable problems with mould growth might have to install active humidity control to avoid serious problems in the future. At the same time, there is a need to reduce the energy used by buildings as argued above. Climate change thus calls for action that adapts the built environment for climate change whilst undertaking mitigation measures, i.e. energy efficiency measures (Davies and Oreszczyn 2012, p. 81).

2.1. The indoor climate compromise

Combining preservation and comfort with low energy use and low cost is for most historic buildings an essential part of sustainable management (Boersma 2009, Staniforth 2014). Technically, this can be described as a question of determining appropriate levels and ranges for temperature (T), relative humidity (RH), light and pollution. In addition, it is about implementing and maintaining technologies for indoor climate control. These include passive measures, such as adding insulation or draught proofing, and active measures, such as ventilation, heating and dehumidification. It is in general more difficult to improve the energy performance of the building envelope in historic buildings, either due to technical difficulties or to limitations because of their cultural values. Hence, indoor climate control is relatively more important for their energy performance, as well as for the potential to reduce energy use. Energy decisions in historic buildings are therefore, to an even greater extent than in other buildings, related to indoor climate control.

There is however little use in treating indoor climate control as if it was distinctly separated from alterations to the building envelope. Decarbonizing buildings calls for an increased use of passive climate control and less use of energy intensive machinery (Roaf 2012). The technical installations needed to control the indoor climate can be intrusive, making permanent damage to the building fabric as well as being inappropriate from an aesthetical point of view. Indoor climate control measures are often implemented in conjunction with measures that improve the hygrothermal properties of the building envelope. Loft insulation, double glazing and draught proofing are common examples also in historic buildings. Moisture from the ground or from rain can sometimes be stopped with capillary barriers, rainwater management, drainage and the like. Such measures to the building envelope affect the building fabric as well as the conditions for the indoor climate control system. However, installations improving the hygrothermal conditions do not necessarily permanently

Figure 1. A reversible glass wall between the nave and the tower in Grötlingbo church, Gotland. Photo by Tor Broström.

alter the historic fabric. This is illustrated by Grötlingbo church on Gotland where a reversible glass wall was built to create a climate controlled zone in the tower (fig.1).

The unit of inquiry for the thesis is not a specific technical aspect, rather, it is the decision processes related to energy efficient indoor climate control in historic buildings. The indoor climate in most of the building stock is governed by requirements for human comfort and health. This has resulted in globally standardized indoor environments and expectations of comfort (Chappells and Shove 2005), and research agendas on energy conservation which take this standardized demand for granted (Wilhite *et al.* 2000, Nicol *et al.* 2012, Lutzenhiser 2014). For historic buildings housing cultural collections the situation is more complex and the demands on the indoor climate are more varied. These buildings are generally not used as dwellings or as offices; hence the demand for thermal comfort is more flexible. The preservation aspect of the indoor climate will have to be balanced against the use of the building and the associated expectations on thermal comfort. The target indoor climate in these buildings is therefore often described as the result of a compromise between preservation of the artefacts and the building on one hand, and the intended use of the building on the other hand (e.g. Michalski 1993, Camuffo 2006, BSI 2012).

Contemporary guidelines, both for cultural collections in general (BSI 2012) and for historic buildings such as churches (CEN/TC 346 - Conservation of cultural property 2011), essentially suggest two fundamental decision-making steps for achieving a sustainable control of the indoor climate in historic buildings. The first step is to find out what the target indoor climate is with respect to the use and preservation of the collection and the building. The second step is to determine how the specification determined in the first step can be achieved in a sustainable way for the specific building and with the resources available.

A conceptual model of the factors that govern what I call *the indoor climate compromise* in historic buildings has been developed for the purpose of this thesis (fig. 2). The model describes how the rationales for having indoor climate control (Benefits/Needs in the figure) and the opportunities and limitations for how the indoor climate can be controlled have to be considered in tandem to determine an indoor climate control strategy. The two steps of defining and achieving a target indoor climate are in this model understood as interrelated rather than as two distinct, successive steps.

The idea of an “ideal” indoor climate for preservation environments, be it for designated museums or historic buildings with vulnerable interiors, has throughout the history of preventive conservation been connected with many practical difficulties (Brown and Rose 1996). The idea as such has been extensively criticized at least since the beginning of the 1990´s. Erhardt *et al.* (1994) showed the different dependencies of relative humidity in a mixed collection and convincingly argued for more flexible set points for RH and T in museums.

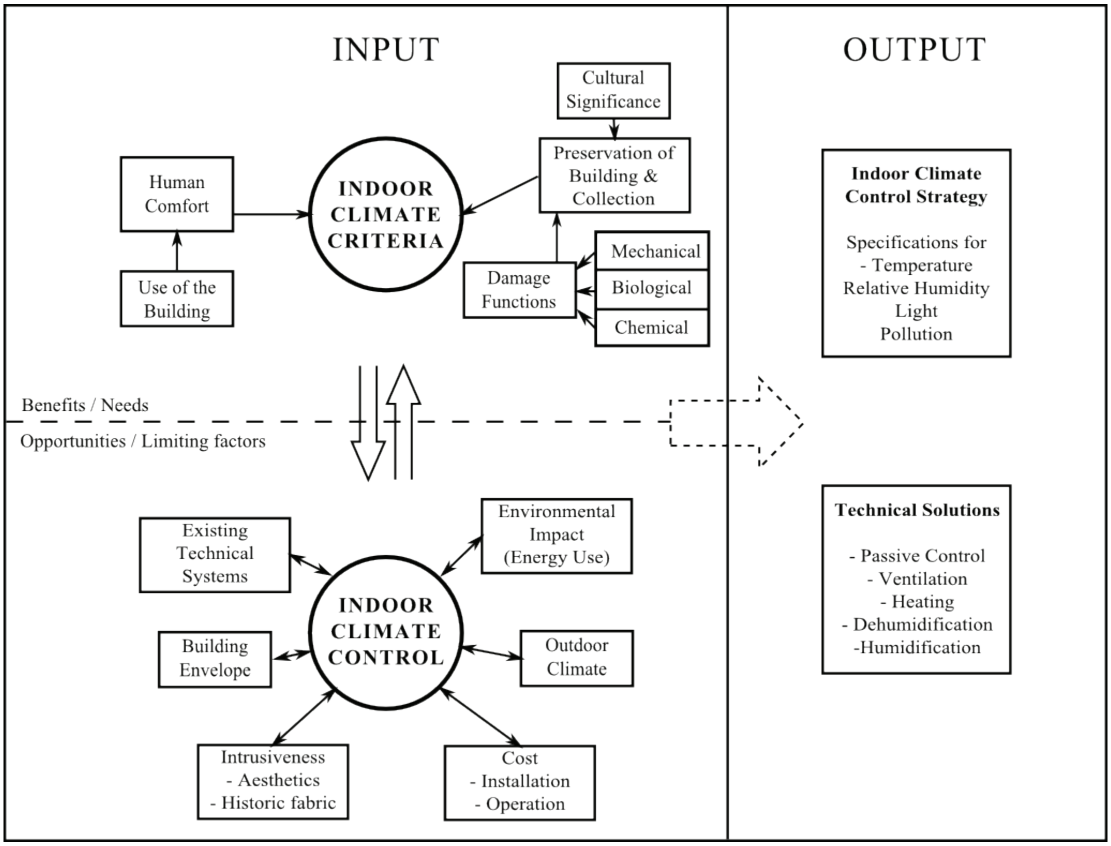

Figure 2. A conceptual model of the indoor climate compromise in historic buildings housing cultural collections.

Hence, already when the preservation aspect is treated in isolation it is evident that the search for an "ideal" indoor climate is one in vain. Characteristically, in the recent UK guideline PAS 198:2012 it is stated that "universally safe" relative humidity or temperature ranges cannot be specified based on the different dependencies related to mechanical, chemical and biological deterioration of different materials.

In sum, there are for a given historic building a number of objectives that have to be balanced when the desired indoor climate is determined. The negotiation of these objectives takes place at different levels of decision making on a continuum from policy making to daily operation. Given the differences in preconditions at each site, and how different objectives are valued, it can be argued that from a normative point of view there should be customized indoor climate control strategies developed for each historic building, and that these strategies should be adjusted as context or priorities are changed. Hence, it would be necessary not to exclude the possibility of negotiating any of the objectives related to indoor climate control when sustainable solutions are sought. Solely focusing on one aspect at a time (e.g. energy use, preservation, cost) limits the complexity of the problem but discard the most important issue: the interplay between the different objectives and thereby the possibility to balance the objectives in a sustainable way.

What makes this issue particularly interesting is the diversity in which the management of indoor climate control in historic buildings is organized. The different roles given to the professionals involved in management, as well as their perceived authority and accountability vary on almost a case-to-case basis. Legnér and Geijer (2015) examine issues of comfort and energy in institutionally managed historic buildings in Sweden during the 20th century. From their historical account it is evident that practitioners struggled to balance competing objectives related to the indoor climate in different ways during the studied period, that the framing of the involved problems were in constant flux and that controversies regarding the roles and responsibilities given to different professional groups never settled. A legacy of this development is today´s diversity in how management is institutionally organized and the heterogeneity of the decision-making processes. This situation, in combination with a lack of legal requirements on both energy performance and indoor climate in historic buildings, also explains the wide range of technical solutions and indoor climate control strategies that are being used in practice.

A collection of international charters, professional codes of ethics and other policy documents is available for practitioners involved in cultural heritage management. There also exists a plethora of guidelines and standards for indoor climate control in historic buildings. Universal principles for how to frame and address problems are inscribed in these kinds of documents, but to use them in practical cases always requires processes of translation and mediation involving various forms of professional expertise (Jones and Yarrow 2013). Such processes of translation apply to all forms of standardization, as standards aim to be universally valid, whereas practice is always specific (Timmermans and Epstein 2010). The way a problem is framed, including establishing its boundaries, is crucial for such translation processes. To bear in mind is that the problem has to be defined before solutions can be sought, and different professional groups will have different opinions about the former. Studies of technological change have revealed that it is the interplay between actors and their resources that shape the way a problem is identified and understood, as well as determine the technical solutions that are used to solve the problem (Bijker and Law 1992).

Not surprisingly, the ability to collaborate among people who define problems differently has been recognized as a key competence in engineering work (Downey *et al.* 2006). The emergence of a manageable problem from a problematic situation is the important first step, in which things to concentrate on are identified and other things are ruled out. Such framing depends on previous references, experiences and how things make sense also for the practitioner (Schön 1983, Weick 1995). How different professionals frame problems differently and interact in energy-related decisions in historic buildings remain important but under-researched questions.

Architects, building conservators, object conservators, curators and other heritage professionals have to collaborate with engineers and building managers regarding energy issues in historic buildings. Problems and solutions are framed in different ways by the involved actors, not least due to conflicts between different cultures among heritage professionals (Legnér and Geijer 2015, Norrström 2015). While such conflicts are perhaps obvious between heritage professionals and engineers, representing two different epistemic cultures, they are also present in the conventional building and construction industry where they have been described as problematic in relation to energy efficiency (Ryghaug and Sørensen 2009). As discussed by Ryghaug (2003) there is a need for many different professional groups with different skills to interact when energy decisions are made in the building design process. E.g. architects in Norway tend to prioritise aesthetics and not be so knowledgeable about energy use in buildings (Ryghaug 2003). This, in combination with their role as co-ordinators of building projects has been described as an important obstacle to improved energy efficiency in new buildings (Ryghaug and Sørensen 2009).

Also among heritage professionals there are differences in how problems are framed, and what aspects of a given issue that is given priority. In Sweden there were in the beginning of the 20th century discussions of how the management of historic buildings should be organized, especially regarding the division of responsibilities between architects and the nascent professional group of building conservators (Wetterberg 1993, Geijer 2007). The institutional organization of built heritage was stabilized in the 1920´s, but tensions between the two professions remain. Whereas architects have tended to prioritize aesthetics and the building as a whole (including its use), building conservators, having their disciplinary roots in the humanities, have been preoccupied with the historic fabric as a source of information about the past. A third group of heritage professionals that often are involved in energy-related decisions are object conservators. Within the profession, there has been a gradual shift from remedial conservation to preventive conservation, and as a consequence indoor climate-issues have come to be increasingly important for conservators (Staniforth 2013). The profession has traditionally had stronger ties to craftsmanship than to applied science, and it is common that conservators struggle to manage a tension in their professional work between a discourse focusing on value-centred preventive conservation and the practical work which often evolves in dialogue with the objects (Richmond and Bracker 2009).

In the Skokloster case described above, it is evident how a seemingly technical question about indoor climate control turns out to be primarily about other things.

The conservation work carried at Skokloster castle between 1967-78 became iconic for the new conservation doxa that developed in Sweden during that time, in which the architect Ove Hidemark played a central role. Hidemark argued for the use of traditional materials and methods, and Skokloster, which had not been equipped with modern technical installations was an interesting case that proved his point. The decisions not to install indoor climate control, not only by Hidemark, but throughout the 20th century, are of course important for the situation today. This legacy is however not merely about the material configurations, but also decisive for how problems are framed and how questions are articulated. The actors involved in decision-making today base their perspectives and their respective positions on previous decisions and actions as well as on personal experience.

The focus of much research in conservation has been on improving the scientific basis underpinning the two-step procedure for decision-making about the indoor climate suggested by contemporary guidelines. The aim has been to be able to give more precise answers to the technical questions involved in the decision-making process. This has been a successful approach in many ways, and the knowledge about climate-induced deterioration, moisture control and human comfort requirements has substantially improved and is continuously improving. However, there has been a focus in this body of scholarship on technical issues: objects, buildings, environments and their interactions. In this thesis, I attempt to explore these seemingly technical issues from an alternative vantage point, where the practitioners responsible for the management of collections and buildings take centre stage. If we go beyond the technical, what kind of questions are raised and what kind of answers do we get? What kind of understanding is needed to progress, what kind of knowledge would the practitioners involved in decision-making benefit from?

2.2. Research aim

The overarching aim of the thesis is *to explore and bridge the gap between research and practice regarding energy efficient indoor climate control in historic buildings*. A guiding hypothesis, which will be discussed in more depth below, is that there is an untapped potential for improving preventive conservation and energy efficiency with the use of existing technology. With a better understanding of phenomena that can explain this potential, I argue that there is a possibility to improve management, policy-making and research design in ways that will facilitate more sustainable practices. This overarching aim is deliberately broad and has been delimitated in a number of ways, resulting in more specific aims. The specific research aims are the result of an evolving understanding of the subject matter, and unfold in relation to the development of the individual papers.

Policies and decision support seeking to improve adaptation of buildings, either to make them more energy efficient or more resilient to climate change, presuppose a realistic understanding of decision processes if they are to be successful (Wilson and Dowlatabadi 2007, National Research Council 2009). I argue that a systematic decision-making process is especially important for energy related decisions in historic buildings and that we have limited knowledge about this process from both a descriptive and a normative point of view. This observation is the rationale for the first specific aim: *To understand how decisions are made and actions are taken in in the specific context of indoor climate control in historic buildings housing cultural collections (paper IV and VI).* In paper IV, I analyse the decision process in a Swedish historic house museum. In paper VI, the organizational context regarding indoor climate and energy related decisions in the Church of Sweden is studied.

The second specific aim concerns the role that uncertainty plays for decisions about indoor climate control in historic buildings. The management of uncertainty is part and parcel of all decision making, but it has during recent years been given more attention in the field of conservation. The use of risk management as a decision framework and the rational programme that this implicates is the focus of the second specific aim: *To explore and discuss how uncertainty relating to decisions about the indoor climate can be managed and communicated to support adaptation of historic buildings* (paper II,V). Paper II identifies and categorizes the major sources of uncertainty when producing predictions about future indoor climate risks in historic buildings. Paper V studies how adaptation practitioners in the Church of Sweden make sense of complex, ambiguous and uncertain information about different indoor climate risks.

Finally, a key question for science-practice interaction is how complex and uncertain knowledge should be communicated to end users. Guidelines, standards and other forms of generic advice play an important role for decisions about indoor climate control. The third specific aim in the thesis is therefore directed towards the role of standardization: *To explore and discuss how decision processes regarding indoor climate control can be supported with standards to achieve a more sustainable management (paper I,III, IV, VI).* Paper I identifies key knowledge gaps of the interaction between the indoor climate and degradation of hygroscopic materials for typical low energy control strategies in historic buildings in a cold climate. In paper III the aim is to discuss the applicability of recommendations for indoor climate control in the case of an unheated Swedish palace. In this paper the building itself is in focus, but it aims to understand the decision context for the management of the indoor climate, and how existing knowledge can be used for risk assessment. Paper IV uses a case study to show the complex route for how new knowledge is transferred into actual organizational decision making. Paper VI is directly aimed at giving suggestions for how standardization can be improved for indoor climate control in historic buildings, using Swedish churches as a case study. It takes as a point of departure the decision context for the management of churches, based on an analysis of the organizational and technical circumstances.

The specific research aims are to varying degrees elaborated in the individual papers. However, partly due to the condensed format of articles, there is a lack of synthesis regarding the overall aim. In this thesis essay I have the ambition to expand on the arguments found in the papers with the aim to both deepen and broaden the discussion of how the science-practice gap can be understood and bridged.

2.3. Research approach and methods

This section outlines the context for the thesis project, describes how the research process has unfolded and argues for the various methodological choices I have made in the individual papers.

An influential context for this thesis work has been the research project "Energy efficiency and preventive conservation through indoor climate control", funded by the Swedish Energy Agency. The Swedish Energy Agency initiated a research programme for energy efficiency in historic buildings - *Spara och Bevara* - in 2008. The objective of the programme was to make historic buildings more energy efficient without damaging their cultural heritage values and at the same time maintain or improve the indoor climate. Experiences from the energy saving programmes initiated after the 1970s oil crisis had highlighted the negative impact from maladapted and insensible retrofitting of historic buildings (Antell and Paues 1981). Energy efficient indoor climate control thus became a focal area for *Spara och Bevara*. The research questions called for an interdisciplinary approach, and researchers with different academic and professional backgrounds were involved already in the beginning of the project (e.g. engineers, conservators, architects).

The design of the *Spara och Bevara* research programme was influenced by experiences made at the department of conservation, Gotland University. Research and consultancy in the field of energy- and indoor climate-related issues in historic buildings had been carried out at the department since the early 1990´s. The research questions were of applied and technical nature, such as how to heat churches in energy efficient ways (Melander and Broström 2008) or how heat pumps can be used for conservation heating (Broström and Leijonhufvud 2008). Despite the focus on applied science, it became apparent that in order to produce practice-relevant knowledge there was a need for a close collaboration between researchers and practitioners. Experiences from these research activities suggested that the biggest hurdle for management was not a fundamental lack of scientific knowledge about how to solve the technical problems, but that much essential knowledge was not used in the management of historic buildings. It therefore seemed that research about conservation science in general, and the research made at the department in particular, did not reach out to practitioners. The origin of this thesis project was this puzzling experience that despite the interdisciplinary, applied nature of the research, based on problems in professional practice, the results were not widely adopted. In turn, this experience indicated that there was a need to achieve a more nuanced and realistic understanding of the complex interaction between science and practice in this field.

2.3.1. *The science-practice gap*

Among both practitioners and scientists there have been recurring discussions about a science-practice gap concerning indoor climate and energy efficiency in historic buildings. The Swedish National heritage board conducted a study in 2010 with practitioners in the heritage sector to map the need for knowledge about energy efficiency in historic buildings. Not surprisingly, all respondents called for more knowledge. However when exemplifying this, they all pointed to a lack of *availability* of existing knowledge. They asked for streamlined accessible information, knowledge repositories, forums, independent consultants, handbooks, good examples, seminars etc. (Altahr-Cederberg *et al.* 2010). A recent UK study came to a similar result that the problem (of making historic buildings more energy efficient) was not a lack of knowledge, but a lack of knowledge utilization: "the main hurdle seemed to be disseminating this [expertise] more widely." (Marie Stuart 2014, p. 190).

One idea underpinning the *Spara and Bevara* research programme was, as outlined above, the existence of a gap between what could be done with existing technology and what was done in practice. More specifically, the potential to both improve preservation and save energy by implementing cost-efficient indoor climate control measures was emphasized. This apparent gap between science and practice, which as we shall see can be theorized in different ways depending on perspective, is at the core of this thesis. It was at the outset of the present thesis work a rationale for the normative and positivistic methodological approach I used in the early phase of my thesis work which aimed at *closing the gap*. Poor, unsystematic and ad-hoc decision-making processes were assumed to be a key barrier to improved end results. There seemed to be a potential to develop tools that could support decision-making, especially regarding how to manage uncertainties. Such improved decision support tools could help practitioners to balance the costs and benefits related to indoor climate control, and in the end result in the implementation of more energy efficient strategies and technologies. This framing of the problem and its solution reflected previous research in conservation science, and resonated with common sense: the science-practice gap could be bridged by improved decision-making.

The thesis project changed focus after the initial phase and I started to be more critical towards my *a priori* understanding of the science-practice gap. My ambition had been to develop normative models that could improve the decision processes that impeded "optimal" solutions to technical problems. Instead, I started to reflect on the extent and nature of the science-practice gap itself. As a result, the apparent "gap" has become less an underlying problem and more a focus of inquiry the longer the thesis work has proceeded; a shift towards *understanding the nature of the gap.*

The science-practice gap has been extensively discussed in different fields of professional practice. The remedies for how to bridge the gap are intimately linked to how the gap is understood, which in turn depends on assumptions about the mechanisms of knowledge transfer. In order to position the epistemological point of departure for the thesis work, I attempt to briefly review the contrasting perspectives found in the literature, along with their methodological implications.

One instance of the gap between science and practice is the “energy efficiency gap”, whose extent and nature has been much debated by energy policy analysts, not least in relation to the building and construction sector (e.g. Jaffe and Stavins 1994, Weber 1997, Shove 1998, Sorrell 2004, Gillingham and Palmer 2014, pp. 32–33, Gerarden *et al.* 2015) . The phenomenon has also been called the “energy efficiency paradox” because of its complex nature and contested status (Gillingham and Palmer 2014, pp. 32–33). The gap is generally understood as an implementation deficiency in relation to economic optimization; as a lack of implementation of cost-effective energy-conserving technologies (Jaffe and Stavins 1994). This difference between optimality and reality has been described as a ”vast untapped potential for negative-cost energy efficiency investments” (Gillingham and Palmer 2014, pp. 32–33). It can be described in slightly different ways depending on if private or societal optimality is considered (Gerarden *et al.* 2015). A “barrier model” is often used for explaining the energy efficiency gap, where different kinds of obstacles, often labelled in terms of market failures, impede end-users from making rational investments in energy saving technologies (Weber 1997, p. 834, Sorrell 2004). This logic extends to policy-making, where policies are legitimate if they remove barriers that distort the market and inhibit profitable energy efficiency investments. However, many economists are sceptical to the very existence of the energy efficiency gap; it is argued that its apparent existence should be traced to modelling errors, for example of hidden costs (Gillingham and Palmer 2014, pp. 32–33).

Although there is little doubt about that there is a potential for cost effective energy efficiency measures in the existing building stock (Guy 2006, p. 645, IPCC 2014), it is important to be aware of that there are alternative ways of framing this problem than in terms of an untapped technical potential and a number of barriers that hamper rational investment. The lack of social considerations in energy policy has received a sustained critique from social scientists, especially towards simplistic characterizations of people as imaginary typical consumers (Stephenson *et al.* 2010, p. 6123, Palm and Reindl 2016, p. 248), which behave rationally and purposively (Wilhite 2013). In this simplistic characterization, it is thought that individuals suddenly will commit to energy saving action if only they have the right knowledge and attitudes (Janda and Parag 2012). The gravity of this critique is emphasized by the fact that the track record of energy reduction policy has been poor (Wilhite 2013, Wilson *et al.* 2015), and that the dominant model fail to explain energy-saving action and energy demand (Lutzenhiser 2014). Guy (2006) disappointedly points out that despite of at least thirty years of research, there is still relatively little knowledge about why proven technical knowledge is ignored, and why energy-saving techniques are consistently avoided.

The energy-efficiency gap is a specific instance, situated in the energy policy discourse, of a broader science-practice gap. What makes it special is the focus on cost-efficiency, and the possibility to relatively easily determine different potentials for energy savings. It is thereby possible to calculate and quantify the gap in terms of an untapped energy saving potential. In most other fields, there is no such opportunity to quantitatively compare ideal and outcome. Still, there are of course gaps between science and practice in all fields, and a common approach is to understand these gaps as problems of knowledge transfer. However, too simplistic understandings based on a linear model of knowledge transfer might frame these problems in misleading ways. Greenhalgh *et al.* (2011) argue that analyses within the field of health care based on simplistic models of knowledge transfer produce similar accounts of problems and solutions. The problems tend to be framed in ways were success factors and barriers are conceptualized in terms of push or pull, where knowledge is thought to be pushed from the supply (science) side, and pulled on the demand (practice or policy) side. An underlying assumption is that science and practice can be separated both empirically and analytically, and that practice consists of a series of rational decisions which potentially can be improved with the help of new scientific results. Solutions are framed as making practice more evidence-based by improving the communication of scientific knowledge (Greenhalgh and Wieringa 2011). Similar framings of problems and solutions are dominating also in fields more related to this thesis such as urban planning (Owens *et al.* 2006), environmental management (Roux *et al.* 2006), climate change adaptation (Moss *et al.* 2013), and the building and construction industry (Guy and Shove 2000, Gluch *et al.* 2013).

Critics argue that the science-practice or science-policy interface is more complex than what the linear model of knowledge transfer implies (Guy 2006, Owens *et al.* 2006, Greenhalgh and Wieringa 2011). The root of this criticism lies in how knowledge is understood. In the linear model of knowledge transfer, knowledge is unproblematically separated from the scientist who produced it as well as from the practitioner who will use it. This view is based on an objectivist approach to knowledge, in which knowledge is a “thing” that can be moved between subjects. The objectivist approach to knowledge has been criticized to downplay the contextual, social and fluid nature of knowledge, not least by social scientists who empirically have studied how knowledge is shared in professional work (Styhre 2011). There are myriad ways that knowledge emerges and gets applied in practice, and there are different ways of framing these processes depending on how knowledge is understood (Evans and Marvin 2006, Styhre 2011). If knowledge is not a transferrable "object", then the gap between science and practice becomes much more complex to understand and to deal with.

The criticism of simplistic accounts of knowledge transfer outlined above echoes much of the criticism raised toward the dominant energy policy discourse. Critics have argued that analyses of the energy-efficiency gap, its causes, and its policy implications are borne out of a stable and shared set of ideas about rationality and consumption that fail to take into account the complexity and heterogeneity of human affairs (Guy and Shove 2000, Wilhite 2013, Lutzenhiser 2014). Guy and Shove (2000) have showed how energy systems in the built environment are understood as primarily technical arrangements, where social aspects are downplayed. Anonymous and purposive end-users, continuously striving to implement cost-efficient energy saving measures, play a central role in this "techno-economic model of technology transfer" (Guy and Shove 2000). Lutzenhiser (2014) claim that this set of ideas acts as an orienting frame for the energy efficiency industry, and provides a vocabulary for analysis which renders the world as stable, predictable and malleable. The techno-economic model is predicated on a separation and imbalance between social and technical aspects, resulting in a framing of the problem where "technical potentials" are restrained by various "non-technical barriers" (Guy and Shove 2000). As a result, the role of science becomes one of determining the technical potentials, while social, political, and cultural factors take the role of "barriers" (Owens *et al.* 2006).

Alternative understandings of energy systems where social considerations play a more important role are reviewed by Sovacool (2014). He concludes that the economic dimension is "only a piece of the puzzle" for understanding the evolution of energy systems, and that tools and approaches from other fields within the social sciences shift the focus of energy research by emphasizing that end users are not passively taking up new technology, but that people and institutions play an active role in the shaping of energy systems through various social processes (Sovacool 2014). Guy and Shove (2000) draw on ideas from the sociology of science and technology in their alternative account of how energy systems evolve. Instead of focusing on individual decision-maker, they emphasize the context in which change occurs. With a set of case studies from the energy efficiency industry, they show that energy practices and technologies are selectively appropriated within specific, local contexts, i.e. that choices and options relating to energy are socially structured.

The literature referred to above shows how there are different ways in how a "gap" between science and practice can be approached, analysed and described. It demonstrates how the techno-economic model of technological change is paradigmatic in energy policy discourse, and that many social scientists are frustrated over its dominant position. The techno-economic model and the alternative socio-technical model(s) originate in fundamental differences in the way the world is understood, they have different methodological implications. The question whether the different models complement or contradict each other is debated. According to Shove (2010, p. 1279), they are not possible to merge: they are like "chalk and cheese". Attempts of triangulation, i.e. making the picture more complete by adding one perspective to the other are, accordingly, doomed to fail (Evans and Marvin 2006, Shove 2010). Others have supported this view, but added that there is a value in that the different models co-exist, precisely because they frame problems and solutions in fundamentally different ways (Wilson and Chatterton 2011).

While the techno-economic model is well aligned with the policy tools offered by strands of social science that focus on individual choice, such as economic theory and behavioural psychology, it is less clear what kind of policy interventions that are supported by alternative (socio-technical) models of technological change (Wilson and Dowlatabadi 2007). Guy and Shove (2000) have argued that the techno-economic model is self-reinforcing in that it sanctions certain ways of conducting research, and authorizes certain forms of possible policy interventions. The model appeals to both sides of the science-policy interface as its core tenets, such as the central role of individual choice, are celebrated by both researchers and policy-makers (Guy and Shove 2000). Furthermore, an important belief sustaining the model is that techniques to promote change that have proven successful in one domain can be transferred to new problems (Shove *et al.* 2012). Undoubtedly, such criticism of the techno-economic model and the policy programme it sustains contains a number of substantial and relevant points. However, a problem with the various socio-technical alternatives is the lack of concrete and realistic alternatives offered for policy-making. As Wilson and Dowlatabati (2007, p. 189) put it: "sociological lessons for intervention design are less generic, less prescriptive, more complex, more diffuse, more gradual, far-reaching, and so, in all senses, less palatable to intervention designers interested in verifiable impacts over short-time periods."

2.3.2. Energy efficiency and cultural heritage values

Conservation is by both practitioners and scholars commonly described as a values-based activity (Pendlebury 2013). The designation of something as "heritage" thereby implies that cultural heritage values are at stake. Accordingly, conservation has been defined as a process aiming to maintain the significance of an object or a place (La Torre 2013). Cultural heritage values are matters of subjective interpretation; they cannot be understood as a fixed property of an artefact, open for inspection. The attribution of multiple and often conflicting values makes decision-making involving cultural heritage values a delicate matter. When different stakeholders have different opinions about what is valuable, it becomes a question of whose values which are most important to preserve. It is also a question of when and where in the decision-making processes that cultural heritage values should be integrated, something which is not obvious (Thuvander *et al.* 2012). The complex relationship between materiality, valuation and conservation practice makes this process even more intricate. Cultural heritage is bound up with the practices that have emerged to preserve it (Jones and Yarrow 2013, p. 6) and conservation actions can modify or create values (Avrami *et al.* 2000). This dynamic has been described by Adams *et al.* (2014, p. 9):

> It is not just a case of identifying pre-existing values that then inform how 'problems' are framed, and when and how heritage science is applied. Rather, the application of science in heritage contexts is embedded in dynamic modes of valuation. The use of scientific techniques to measure, understand and control material transformation is informed by these values, but these very processes also have the potential to change those values.

The contested and subjective nature of cultural heritage values, and the complex relationship between valuation and conservation practice make it evident that cultural heritage values cannot be understood as static attributes of an historic building. An implication of this is that it seems unlikely that it is possible to empirically establish the extent of a gap between science and practice related to energy decisions in built heritage. The many competing objectives related to energy decisions in historic buildings, as well as the importance of (contested) cultural heritage values, make actual decision making far off the cost-benefit calculations presupposed in much theoretical work about energy efficiency in buildings.

Furthermore, I would question the notion of an energy efficiency gap in historic buildings even as a theoretical construct, when what is judged as a plausible energy efficiency measure is dependent on a subjective valuation of cultural heritage values, a valuation which is bound in time and place. Such an analysis requires that historic buildings are considered to be mere technical arrangements, stripped bare of social connotations. As a consequence, it also seems doubtful to characterize cultural heritage values as "barriers" to energy efficiency in the building stock.

2.3.3. Methodology

In the light of the above review, I conclude that there are competing and multiple understandings available of the involved phenomena, understandings which are not possible to merge. While I acknowledge the advantage with the techno-economic model in that it is well aligned with existing policy options, I find it inadequate for understanding the decision processes which are covered in the present thesis. Instead, I use a socio-technical lens, in which both knowledge and actions are understood as situated in specific material and social contexts. The most important methodological implication of this is the need to understand the specifics of the situated actions where problems occur. Only then it is possible to seek solutions to the problems rooted in practice. It has been claimed that to understand the complex and interpretative character of much energy-related decision-making, there is a need for detailed ethnographies (Lutzenhiser 2014). Thollander and Palm (2015, p. 5699) elucidate how a situated action perspective can be useful for understanding energy-related decisions by referring to an imagined meeting:

> Rather than depending on a goal in a document or procedures in a standard it [the outcome] will be dependent on which actors participate in the meeting. The actors attending a meeting will most probably not have memorized all policies, standards and procedures that exist in the organization. They will base their input and contribution to the discussion on energy efficiency on their culturally embedded understanding of how to act, what choices are given in different contexts and what decisions seem to be suitable in different settings. /…/ The participants in meetings take different roles, and the roles actors have in one group will differ from their roles in another group. Actors take different roles, and in this sense too roles are situated.

In paper IV, I use a detailed qualitative case study to understand how the actions, roles and rationales among different professionals are situated in the specific material and social context of an historic house museum.

Borne out of the normative aim of improving professional practice, this thesis is problem-driven rather than theory-driven, and therefore an example of practice-oriented or *practice-based research*. Practice-based research involves inquiry of procedures of professional practice and aims at utilizing research knowledge to enhance the development of practice and policy (Marshall 2010). It has its greatest benefits in areas where traditional research approaches have failed to have an impact on policy and practice because of problems with knowledge uptake - a result of that practitioners are unable to translate traditional research results into recognizable and adoptable activities (Marshall 2010). Generalizable theory development is played down in practice-based research; the produced knowledge is contextual and contingent.

Contemporary conservation practice, with its combination of technical, social and interpretative considerations, is by nature *interdisciplinary*. As a field of practice, its focus has changed “from single object treatment to broader preservation strategies”, a change which has forced conservators to “actively adopt an interdisciplinary approach“ (Scott 2008, pp. 121,125). Several of the topics that relate to the research questions in this thesis are by themselves of interdisciplinary nature. It has been argued that issues of paramount concern for sustainable development such as risk, energy and climate change cannot be reduced to a single discipline or a fixed set of theories, they should be understood by the ‘philosophical, methodological and normative diversity’ characterizing environmental social sciences and humanities (Castree *et al.* 2014, p. 763). My position is that the issues discussed in the present thesis can only be thoroughly understood by an interdisciplinary approach, i.e. a combination of technical and social perspectives.

Conservation has a long history as a *field of practice*, but it is only recently that it has been established as a *field of inquiry*[1]. The theories and methods guiding knowledge production in conservation have not settled in the same way as in more established disciplines. Conservation science has exploited the natural sciences to produce technical knowledge relevant for practitioners, and scholars from established academic disciplines in the social sciences and humanities have observed the practices within the cultural heritage field through various theoretical lenses in order to understand the involved social processes. However, for the reflexive inquiry needed to study the field of conservation from within, and thereby produce relevant knowledge for practitioners, there is no given methodological roadmap. I argue that to produce practice-relevant knowledge there is a need to connect empirical findings, related to problems in practice, to existing theories through an informed dialogue with established disciplines. In that sense, the thesis is *transdisciplinary* as it has the ambition to solve real-world problems by collaborating with both practitioners and scholars from different academic disciplines (Spreng 2014).

Transdisciplinarity emphasizes the need for a dynamic relationship between science and the world being studied, including the higher degree of stakeholder involvement in the formulation of research questions implied by "mode 2" knowledge production (Nowotny *et al.* 2001, Scholz and Binder 2011). In this case, the *Spara och bevara* research programme has been at the forefront, with a high degree of stakeholder involvement from the outset. Transdisciplinarity also emphasizes the need to involve values in the research process by not refraining from questions such as "What is it we want to do?" and "How should we do what we want to do?" (Spreng 2014).

The ambition with the present thesis is to produce knowledge that is usable for the practitioner or the policy-maker. Based on the experiences from the *Spara och bevara* research programme, it was evident that good judgment among practitioners always played an important role in the application of scientific knowledge in real life situations. A key methodological question for this thesis has therefore been what kind of research design that produces knowledge that facilitates such good judgment. An increasingly influential version of practice-based research is the phronetic social science programme laid out by Danish planning researcher Bent Flyvbjerg (2001). Flyvbjerg is interested in how to produce the kind of knowledge Aristoteles labelled *phronesis*, the type of value-rational, practical wisdom needed for good judgment. With the ambition to produce knowledge relevant for practitioners, phronetic social scientists have to engage in detail in the complexities of the studied phenomena to understand specific practices. Flyvbjerg argues the case study is the key methodology for achieving this aim, and that the end result – the case study itself – can contribute to phronesis by way of example.

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[1] I am indebted to Halina Dunin-Woyseth for the distinction between conservation as a 'field of practice' and a 'field of inquiry'.

To wrap up the methodological development in the thesis, there is a continuum relating to both how theory is used and the object of inquiry. What ties the approaches together is an emphasis on how knowledge is, or can be, used in decisions which aim to balance conflicting needs, specific for the individual case. The double aim of the thesis to both solve and understand problems in practice is evident in all papers. It is elaborated through rather different theoretical lenses, spanning from the practical, which focuses on technical aspects, to the critical, which focuses on socio-technical aspects. In turn, these have required different methodologies. The benefits or downsides of this way of moving between epistemological perspectives are up to the reader to evaluate. However, I am sure that if I had chosen only one path instead of trying to embrace both, the outcome would not have been the same.

In paper I-III the studied phenomena are physical matter and their properties, and both the research questions and the applied methods are typical for the positivism generally found in conservation science. Paper I and II are reviews, while Paper III is the result of a quantitative case study, focused on technical questions.

The socio-technical contexts of decision-making are the focus of paper IV-VI. Paper IV and V study how decision-makers attempts to make sense of issues related to indoor climate control in specific contexts. Paper IV is an explorative qualitative case study, in which I try to understand the complex decision context for indoor climate control in a historic house museum, and how norms, material configurations and practices preconfigure choices and actions. Paper V uses qualitative interviews to understand how practitioners make sense of risk information related to climate change. Paper VI is partly descriptive, partly normative in the attempt to discuss how standardization for indoor climate control in Swedish churches can be improved on the basis of an understanding of the technical and organizational context. While paper IV studied the decision context related to a single building, papers V and VI have a wider, organizational perspective.

2.3.4. Summary of methods

In order to give an overview of the different methods used in the present thesis, this section briefly outlines the different methods used in the individual papers. For a more comprehensive description of each method, the paper in question should be consulted.

Paper I: Reviews the literature on mechanical damage to hygroscopic materials with a focus on the indoor climate in unheated and intermittently heated historic buildings in the Nordic climate.

Paper II: A literature review identifies and describes the sources of uncertainty in the prediction of future indoor climate risks in historic buildings. The major sources of uncertainty related to climate change modelling, building simulation and damage prediction are covered. This paper also involves a conceptual discussion of decision-making strategies to cope with uncertainty based on the literature of climate risk management.

Paper III: The hygrothermal indoor climate in a Swedish palace was extensively monitored for a period of two years (2008-2010). The building had practically no active indoor climate control and the monitoring campaign was set up to clarify how the buffering properties of the building envelope attenuated outdoor fluctuations in temperature and relative humidity. A logbook was used to gather information about events that could influence the indoor climate (opening/closing doors, cleaning etc.). RH and T were measured every hour for a period of two years in 27 rooms. Air exchange was measured quarterly in selected rooms using tracer gas and diffusive sampling. The results of the monitoring was used for applying and discussing existing approaches to go from measured data to establish a target indoor climate for the building.

Paper IV: This paper is based on a qualitative case study in a Swedish historic house museum. The varying perspectives on indoor climate control held by individuals involved in the management of the museum were the focus of semi-structured interviews carried out between 2009 and 2012. Each interview lasted between one and three hours. All the interviewees either took part in decision making concerning the indoor climate or were affected by it in some way. Topical questions during the interviews revolved around how the interviewees described and evaluated the current indoor climate, and on how decisions about indoor climate control were made as well as their own and others' influence on this process.

Paper V: The European Climate for Culture project produced risk maps of future indoor climate related risks in historic buildings. In this paper, I use qualitative interviews to understand how architects and engineers involved in the management of churches in Sweden interpret some of these risk maps. In addition, method development was a part of the transdisciplinary approach used in this paper as the aim was to develop a methodology for how climate risk information produced by Climate for Culture and other impact assessment studies can be communicated to end-users.

VI: This is mainly a conceptual paper built on a mixed methodology including a qualitative interview study, monitoring of indoor climate in churches and a literature review. The Swedish church was used as a case study, and material from the same interview study as in paper V was used to understand the organizational context for standardization. Extensive monitoring of the indoor climate in Swedish churches performed during the *Spara och Bevara* programme was used to discuss different ways of standardizing indoor climate control. Standards for indoor climate control in historic buildings were reviewed.

2.4. Summary of papers

Paper I. *Preventive conservation climate in historic buildings – some gaps in the knowledge.* This paper was originally published in Swedish in the Nordic journal Meddelser om konservering with the title *Bevarandeklimat i historiska byggnader: några kunskapsluckor.* It reviews the literature regarding mechanical damages to hygroscopic materials caused by fluctuations in humidity and temperature. Knowledge gaps which are critical for assessing risks with low energy control strategies are identified by using two hypothetical case studies of historic buildings in Sweden.

The review suggests that for certain situations when the indoor climate deviates from conditions commonly found in museums, there is a lack of robust scientific evidence to inform risk assessment. Two examples related to energy use in historic buildings in Sweden are low temperatures and intermittent heating. First, in buildings which are not heated for thermal comfort, it is possible to mitigate high relative humidity during winter with a low amount of energy. In practice, this implies low minimum temperatures for conservation heating and even lower if dehumidification is used. The question in this case is what effect the low temperature has on the risk for mechanical damages under these circumstances. Second, there is a long tradition of using intermittent heating in, mostly rural, churches in Sweden. By quickly heating the church it is possible to combine thermal comfort and low energy use. However, the heating causes humidity and temperature fluctuations of high amplitude and short duration which might cause mechanical damage to artefacts. The question in this case is if it is possible to assess the risk for damage caused by intermittent heating. The review concludes that there is both a need and potential to improve the knowledge base in order to answer these two questions in a satisfying way.

Paper II. *Uncertainties in damage assessments of future indoor climates.* This paper is based on a literature review and aims to identify and qualitatively describe the main uncertainties in the risk maps generated in the Climate for Culture (CfC) project. The information produced by CfC is not qualitatively different from other kinds of predictions used in decision making about indoor climate control. However, the extra modelling step which involves projections of climate change adds complexity and uncertainty. In the paper, the sources of uncertainty in each step of the modelling process are identified and categorized by their dominating nature: epistemic, aleatory or ambiguous. Uncertainties propagate through the modelling process in an ”uncertainty cascade”, which begins with uncertainties related to climate change impacts, continues with building simulation and finally damage functions. It is concluded that the relative level of uncertainty for each modelling step need to be further studied, and that deterministic ”best guess” approaches, such as the one used by the Climate for Culture-project, have severe limitations as the uncertainty range is largely unknown. Also the worst-case approach often used by conservation scientists to establish ”safe” limits have drawbacks when used for the risk assessments that inform policy making.

Drawing on the literature on climate change adaptation, this paper also discusses how a high level of uncertainty can be managed and communicated in decision processes, and what viable alternatives there are for modelling. A conclusion which is important for the rest of the thesis is that adaptation decisions have to be made despite deep uncertainty, and that ambiguity related to worldviews and values is the cause of a considerable portion of the unresolved uncertainty.

Paper III. *The indoor climate in Skokloster Castle*. The objective of this paper is to analyse the indoor climate in Skokloster castle, make a risk assessment and to propose low-energy interventions to improve the indoor climate with respect to the long term preservation of the collection. A key question is the usefulness of recommendations for indoor climate control of collections for an unheated historic building in Sweden.

The indoor climate of Skokloster is characterized by high thermal inertia and high, fluctuating, relative humidity. The passive function of the building envelope in reducing fluctuations varies significantly between individual rooms. Despite the passive control provided by the building envelope, the fluctuations and levels of temperature and humidity are well beyond what is considered safe in the literature. Hence, instead of recommending levels and limits found in the literature, we analyse how the energy use is influenced by different target levels, visualized with duration graphs. A minimum level of climate control, consisting of only passive measures, is a possible solution but active control is necessary to avoid the biggest risk: mould growth.

A conclusion of the study is that the risk assessment is the weak link when trying to bridge indoor climate measurements and technical measures to improve the indoor climate. In relation to the thesis, this case study is exploratory in that it identifies limitations with the standard toolkit for indoor climate control, and raises a number of questions related to the use of standards. This study has been instrumental for the development of the rest of the thesis in that it shows the limitations of a process which relies on science alone for generating solutions.

Paper IV. *Rethinking indoor climate control in historic buildings: Negotiated priorities and discursive hegemony at a Swedish museum*. In this paper, co-authored with social anthropologist Annette Henning, we show the necessity to complement the dominant technical approaches of indoor climate control with research that take a wider interest in specific contexts, social practices, and negotiated decisions. This paper takes stock of the results from the previous papers in the thesis, in which the technical foundation for a risk-based approach to decision-making about the indoor climate have been discussed. In this paper, the social aspects take centre stage, and it is shown how these are paramount for enabling change towards more sustainable technical solutions. It uses a qualitative case study of decision making in an historic house museum to illustrate how the interactions between perceptions and experiences of different professional groups are pivotal for the management of the indoor climate.

While physical properties and the limited knowledge about these were the focus for paper I-III, in paper IV it is individual actors and their perceived life-worlds that are the object of inquiry. The analysis draws on research that criticizes conventional accounts of decision making in organizations which fail to recognize the social nature of decisions. The findings show how discussions among social actors and the way their respective priorities are negotiated are essential features of the management of the indoor climate and have a strong impact on the ability to modify it. Subtle but important differences in how different professionals interpret and rationalize the means and ends of cultural heritage management prove to be important for the discourse about the indoor climate.

In relation to the rest of the thesis, this paper shows the shortcomings of reducing the involved problems to technical matters only, or to assume some variables (such as comfort) to be static and given facts – such approaches clashes with the negotiability that is part and parcel of every real situation, and restrains the set of possible solutions to the problem.

Paper V. *Making sense of climate risk information: the case of future indoor climate risks in Swedish churches*. The predominant methodology used to assess the impact of climate change on cultural heritage is a top-down approach where the outcome is a projection of future risk, such as the Climate for Culture-project. In paper II the uncertainties generated in such projections were identified, and it was concluded that there was an extensive, but unquantified, amount of uncertainty in the output. This overall question for this paper is how such projections should be communicated to be useful for decision makers at different levels, given the complexity, uncertainty and ambiguity of the product.

Previous research has pointed out both the need to communicate the uncertainties in climate change impact assessments as well as the many difficulties involved in such efforts. A better understanding of how complex and uncertain scientific knowledge is interpreted and used by professionals is much needed. A first step is to test whether adaptation practitioners at all render the risk information as useful. The objective of the paper is twofold: the major objective of the paper is to explore and understand how the generic, ambiguous and complex climate risk information produced in the CfC-project is interpreted by heritage decision-makers. A secondary objective is to develop a methodology for how to select adaptation-relevant parts of the risk information produced by CfC and pre-test its dissemination to a specific target audience.

By using interviews, I study how architects and engineers involved in the management of churches in Sweden interpret information produced in the Climate for Culture project about the impacts of climate change on historic churches. The results show that the risks were interpreted and assessed in quite different ways by different individuals, largely dependent on their pre-understanding and familiarity with the individual risks. The magnitude of change and the lack of uncertainty estimates seemed to be subordinate to the overall impression of the information as being credible and salient.

The major conclusion is that the dissemination of risk information, also from projects which at the outset have aimed at producing knowledge relevant for end-users, should be both customized and tested in collaborative efforts by stakeholders and scientists.

Paper VI. *Standardizing the indoor climate in Swedish churches: opportunities, challenges and ways forward.* Standards and guidelines are considered to be essential for knowledge transfer by both practitioners and researchers in the cultural heritage field, but how they are used and how effective they are in facilitating sustainable management is not well studied. The overall problem addressed in this paper is how scientific results and best practices concerning indoor climate control effectively can be shared to end-users.

Standardization for indoor climate control in historic buildings has recently taken a new direction with the production of standards and guidelines that focus more on decision processes than outcomes in terms of universal target levels. The objective of the paper is to explore and discuss how recent standards of the environmental management of collections in general and European standards of the indoor climate in churches in particular can be used by the Swedish church to facilitate a sustainable management of churches. The specific technical and organizational context of Swedish churches is identified in order to understand the needs and challenges for standardization. A mixed methodology is used based on interviews with engineers and heritage professionals in the Swedish church and extensive monitoring of the indoor climate in Swedish churches. The results show that the development of procedural standards solves some of the problems related to the conventional outcome-oriented approach by opening up for a wider set of solutions. However, available guidelines are difficult to apply and integrate in the existing management of churches due to organizational constraints and limited resources. It is suggested that generic guidelines have to be customized to specific decision contexts to be useful. The main conclusion is that to improve standardization there is a need to evaluate to what extent guidelines and standards are adopted, how they are used and how they affect management.

In relation to the rest of the papers in this thesis, this paper tries to bridge and integrate the positivistic, technical and solution-oriented approach taken in paper I-III with the epistemological perspective of paper IV and V, which uses a social lens to understand the involved problems. By looking at standards as one among many instruments for knowledge sharing, and by recognizing the importance of a pre-understanding of the decision context for the development of effective decision support, the discussion on the role and nature of standards for indoor climate control is broadened, and a number of concrete ways forward both for standard makers and standard users are suggested.

3. Background: the dominating research agenda

> There is something inelegant in the mass of energy-consuming machinery needed at present to maintain constant RH and illuminance, something inappropriate in an expense which is beyond most of the world's museums. (Thomson 1986, p. 267)

The aim of this section is to outline and critically examine previous research which has addressed decision-making about indoor climate control in historic buildings. By necessity, it will partly be an historical account but the ambition is to focus on contemporary research. The focus is on the development of standards[2] for indoor climate control, as standards have played, and continue to play, an important role for conservation practice. They are also considered to be essential for knowledge sharing by both practitioners and conservation scientists. This does not mean that standardization comes without disadvantages, or that knowledge sharing could be organized without the use of standards. As an example, Legnér and Geijer (2015) have shown how norms and standards of the indoor climate became problems rather than solutions for managers of historic buildings in 20th century Sweden.

Relative humidity (RH) is often considered the crucial parameter for the conservation of material and objects, as it plays a major role in numerous deterioration mechanisms (Camuffo 2014). Temperature (T) plays a less important role for conservation, but it has to be considered regarding human comfort. As RH is largely dependent on T, it has been natural to combine

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[2] The term standard is used in this thesis as defined by Brunsson *et al.* (2012, p. 616):"…a rule for common and voluntary use, decided by one or several people or organizations." This is a broader definition than the official ones used by e.g. ISO. The definition includes documents issued by international standardization bodies as well as institutional guidelines and recommendations in handbooks.

these two parameters in standardization.

Indoor climate standards for museums and archives have never been perceived as realistic for historic buildings housing valuable collections such as historic houses and churches, even though they have sometimes been looked upon by practitioners as ideals to strive for. The common way to address historic buildings has been to suggest a wider target range[3]. The development of indoor climate specifications for historic buildings has been based on and related to the development of museum standards and therefore it is of interest to outline the genesis and evolution of museum standards.

3.1. Standardization of the indoor climate in museums and the development of the de facto-standard

The history of recommendations for humidity control in museums shows a trend of an increasingly controlled environment, conveyed in a series of specifications, recommendations and handbooks throughout the twentieth century (e.g. Brown and Rose 1996, Erhardt *et al.* 2007, Michalski 2009, Legnér 2011, Martens 2012, Luciani 2013, Atkinson 2014). An important concept influencing this development was that humidity fluctuations were known to cause mechanical damage. The details of this relationship were not well understood, which led to the precautionary conclusion that a more stable environment in terms of RH was preferred to a less stable one (Staniforth 2014).

Recommendations of set points in standards and guidelines have not been decided exclusively on what is best for the preservation of artefacts. Yearly averages and ranges have been set based on a, sometimes opaque, combination of preservation requirements, thermal comfort requirements and, characteristically, what has been reasonable to control with available technology at the time (Thomson 1978, Bickersteth 2014).

Standards have not been developed in isolation and that there has been a co-evolution of climate control practices, technical innovations, norms and standards during the twentieth century. More refined environmental control strategies have gone hand in hand with innovations in control and monitoring technology. An array of innovations was introduced in museum buildings during the twentieth century: increasingly more powerful HVAC-systems, thermal insulation, vapour barriers, electronic data loggers, etc. Standards have reflected this development – serving as both a cause and effect of increasingly more uniform control practices.

The de facto-standard of a stable indoor climate around 50 % RH and 20 °C has been, and still is, the focal point for the sometimes heated debates around set points for RH and T in museums (Cassar 2011, Burmester and Eibl 2013, Bickersteth 2014, Staniforth 2014). The origin of these numbers can be traced back to the early 20th century (Brown and Rose 1996),

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[3] E.g. Thomson (1986), Fjæstad (1999).

but the often referenced modern source is the widely used handbook *The Museum Environment* by Garry Thomson (1978). It is difficult to overestimate the impact of this '50/20' recommendation on indoor climate policies and practices in today's museums.

The highest level of control has been recommended only for deliberately designed museums and archives, where the hygrothermal properties of the building envelope make tight control less demanding, or for showcases with microclimate control. Despite this, huge efforts have been made to achieve the highest standard of control also in buildings with inferior hygrothermal performance, sometimes with considerable side effects and often without success (Martens 2012). This is not exclusively a problem for historic buildings, but also for newly built museums which have been designed with little thought on hygrothermal performance (Padfield and Larsen 2004).

What were intended as flexible guidelines have been used as strict specifications, a transformation explained better in terms of factors external to the original guidelines than by the intention of the standard makers. The recommendations in *The Museum Environment* as well as other publications have been used in ways that arguably were neither foreseen nor desired. One example is that recommended average set points have been suggested to be adjusted to the local outdoor climate.[4] However, in the de facto standard of 50/20 the exemplified average set points have been transferred without such modification. The interpretations of recommendations have therefore pushed the development toward a more uniform notion of the ideal museum environment.

Suggested targets have, even if they have been intended as mere examples, been used as blueprints. Weintraub (Weintraub 2006, p. 196) has described this transformation as the "reframing of informal environmental guidelines into formal and precise environmental specifications.". Weintraub (2006) argues that there is a mismatch between the linearity of building projects and the iterative process needed for the negotiation of different aims for climate control. Planning processes which relies on demand specifications at an early stage has therefore encouraged a prescriptive use of standards which was not intended by the authors of guidelines. Weintraub (2006) also emphasizes the role played by traveling exhibitions in the convergence of demands on the indoor climate. Traveling exhibitions require agreements across institutions over the world, which narrow down the range of possible local solutions. The strictest control possible has been the norm in contractual agreements for travelling exhibitions, however not always in practice (Ashley-Smith *et al.* 1994). Given the often high economic values at play in international loans of art works there is little to lose in requiring nothing but the safest possible conditions.

The spread of the de facto-standard could be understood as a technological lock-in process, which is now difficult to reverse.

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[4] E.g. Thomson (1978), ASHRAE (2011).

The ability to control indoor conditions regardless of outdoor weather has been fundamental for establishing the modern notion of a museum: it has made it possible to use collections in new ways. The daily routines of handling and displaying museum objects have therefore to some extent been shaped by the energy-intensive technologies which are now being questioned.

The very existence of standards, and how they have been formulated, might have played a significant role in shaping practice as standards in themselves form our expectations. Shove and Moezzi (2002, pp. 265–271) argue in connection to standards for thermal comfort that "the very existence of definable standards is instrumental in carving out territories of convention and expectation" and ask, rhetorically, if "energy efficiency standards have the perverse effect of reducing socio-technical diversity and thereby fostering a global monoculture of consumption?".

Standardization entails processes of quantification and formalization that are powerful in transforming practices and norms (Espeland and Stevens 1998, Brunsson *et al.* 2012). Healy (2008) describes how the Comfort Chart and its successors have been instrumental for the success of air-conditioning and the homogenization of human comfort. The Comfort Chart shows a quantification of thermal comfort in terms of T and RH. He argues that:

> The power of numbers, however, derives not merely from how they facilitate 'evaluation and judgement', but also from how they are regarded as the exemplary means of ensuring objectivity and securing against arbitrariness and bias. (Healy 2008, p. 315)

The history of standards for humidity control in museums shows a series of such powerful numbers, and clearly they have been regarded as ideals. Michalski (2009, p. 1) suggests that the concept of a few universal targets might have been successful in the museum world because of the mere simplicity of the approach; that they 'make life much easier' for museum professionals. Quantification and commensuration are powerful ways of changing perceptions of the world (Funtowicz and Ravetz 1990, Porter 1995, Espeland and Stevens 1998, Espeland and Stevens 2008). It is symptomatic how the same numbers have reoccurred during the history of standards for humidity control (Brown and Rose 1996). The 50/20 target of the de facto standard seems to have become a cognitive anchor (Tversky and Kahneman 1974) in discussions about preservation environments.

3.2. Problems with the de facto-standard

Standards and guidelines have played an important role for the formation of a globally homogenous conception of an ideal museum environment, a notion which is considered to be increasingly problematic considering the energy transition needed for a low carbon future. Shove (2002, pp. 8.273) addresses this problem in relation to standards for thermal comfort, echoing the quote from Thomson above:

> Now embedded in standardized codes, factors which started as a set of engineering conventions - the set-point, the number of air changes per hour, the comfort zone - have become the norm for building users and building designers alike. This is seriously bad news in environmental terms for it is difficult, sometimes impossible, to meet these exacting standards without the use of energy intensive heating and cooling systems. Not only that, the presupposition of control is central to the development of standards of this kind.

The de facto-standard consisting of low fluctuations around 50 % RH and 20 °C T has been substantially criticized for a lack of scientific support (Holmberg 1995, Erhardt *et al.* 2007, Martens 2012).

> /…/ the climate specifications typically used in museums for temperature, RH, and allowable RH fluctuation ultimately seem to derive from three basic bits of data- the human temperature comfort zone; the average RH in the National Gallery, London, as determined by weighing blocks of wood; and the practical mechanical limitations on RH control in museums. The climate recommendations thus "derived" have since been extended, solidified, and modified with little more justification.(Erhardt *et al.* 2007, p. 13)

The problem is not that adhering to the standard will cause damage (although many materials will deteriorate slower in a drier or colder environment), but that there are negative side effects associated with the strict control. In short, the problem with the de facto standard implying minimal excursions from set points at around 50 % relative humidity and 20 ºC is that it requires a level of indoor climate control that, for many museums, is not perceived as environmentally sustainable due to the amount of energy used (Boersma 2009, Staniforth 2014).The balance between preservation and use of collections and buildings have dominated discussions about indoor climate control. However, energy conservation and decarbonization have become increasingly important among both policymakers and practitioners (Boersma 2009, Cassar 2011, Silva and Henderson 2011, Barthel-Bouchier 2013, Staniforth 2014).

Strict indoor climate control can be associated with several negative consequences in addition to the environmental impact. The running and installation costs of heating, ventilation and air-conditioning (HVAC) systems are considered problematic for many museums (Artigas 2007). The technical installations needed can have both aesthetic impact and require interventions in the historic fabric. System failure, e.g. malfunctioning dehumidifiers, might cause risky humidity excursions as well as risks of fire and water leaks. The building housing the collection might suffer from moisture problems in the building envelope due to humidification.

In addition to the above risks associated with tight control, it has been argued that the de facto standard is unrealistic to achieve, especially in older buildings and that an adherence to the standard at all times is a matter of hypocrisy (e.g. Ashley-Smith *et al.* 1994, Holmberg 1995). However, the extent of the involved risks is debated and there are museums which have been able to combine a stable climate with relatively low energy use (Burmester and Eibl 2013). Furthermore, the preservation requirements have to be balanced with demands for thermal comfort - which proves to be a difficult task even in theory (La Gennusa *et al.* 2008).

Apart from the above mentioned problems, there are more fundamental problems with the de facto standard, and all other standards suggesting single, fixed numbers. Universal advice regarding set points for indoor climate parameters – the "ideal climate" approach – have substantial shortcomings (Erhardt and Mecklenburg 1994, Michalski 2009, BSI 2012, Staniforth 2014). Different materials and constructions have different needs in terms of what is best for their preservation (Erhardt and Mecklenburg 1994), which means that there is no single set point that will be optimal for the preservation of all objects in a mixed collection. The opening paragraph of the section on RH from UK PAS 198:2010 summarizes this critique of the idea of a universal, "ideal" target RH range:

> Relative humidity influences the rate of many deterioration mechanisms: chemical, biological and physical. Variations in RH can also cause deterioration. Given the different dependencies on RH of these mechanisms, and their variation between collection items, a universally safe RH range and permissible variation for collections cannot be specified. In the past, attempts to extrapolate a universal safe zone by providing conditions required by sensitive objects for all collection items have often resulted in unsafe conditions for atypical collections, as well as leading to an unsustainable use of energy. (BSI 2012)

Outside of the museum context, the preservation aspect of climate control has, if not been neglected, received limited attention in many historic buildings. Other factors have been more salient for the control strategy, such as thermal comfort or cost. In cases where a more sophisticated approach has been sought it has been difficult to apply standards. The targets of the de facto standard have been too ambitious for most buildings and have been perceived, if at all, as unachievable ideals. This is partly due to the fact that the possibility to control the indoor climate often is limited due to the hygrothermal properties of old construction. This situation has sometimes led to an all-or-nothing approach to climate control, where some objects of the collection have been put in controlled showcases or controlled rooms, while other objects have been left in an environment where little attention has been paid to the preservation aspect. The de facto standard has in this way inhibited indoor climate control strategies that are customized to various building types, uses and geographic locations.

3.3. Recent development

While early experiments and practical experience had been able to identify conditions that could be considered safe (Brown and Rose 1996), they had not been able to estimate safe ranges for mechanical damage. In the 1980´s, new research at the Smithsonian institute showed the possibility to set a range of allowable humidity fluctuations based on how individual materials responded to humidity fluctuations in laboratory tests (Erhardt and Mecklenburg 1994, Erhardt *et al.*

2007, Bratasz 2013). These new findings together with the increasing running costs for HVAC-systems started a debate about the "relaxation" of the prevailing tight recommendations for humidity control.

The scientific community is now focused on a better understanding of damage functions and to replace the de facto standard with improved recommendations based on scientific evidence (Strlič *et al.* 2013). The overarching approach is to identify safe limits which can be transferred to end users in standards and guidelines. Laboratory research on the role of temperature and humidity fluctuations on mechanical damage has followed up and largely validated the pioneering methods used by Mecklenburg and colleagues at Smithsonian (Bratasz 2013), but there is still a debate about the usefulness of the methodology, especially among practitioners (Cassar 2011, Bickersteth 2014). Critics have argued that it is a general problem that the scientific results, apart from being inconclusive, are based on laboratory experiments rather than field studies (Bickersteth 2014).

The recent development concerning standardization has been a gradual shift away from definite guidance in the form of universal numbers toward more flexible approaches. The recent European standard EN 15757:20109 Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials takes an innovative route by using the historic indoor climate as a reference for establishing allowable short term fluctuations based on that artefacts are less vulnerable to fluctuations that they have already been exposed to (Bratasz *et al.* 2007). The ASHRAE handbook provides for flexibility in the end result by suggesting that control targets are set in relation to the potential to control the building and the level of risk aversion of the user. Even though the ASHRAE handbook includes a chart with control targets, the length of the explanatory text suggests that its essence is not in the suggested numbers, but as a reference for individual decision-making.

The European standard EN 15759-112 Guidelines for heating churches, chapels and other places of worship and to a greater extent, the British PAS 198:2012 Specification for managing environmental conditions for cultural collections are focused on the decision process. Both of these standards describe a process for how to establish a target indoor climate, but do not suggest any numbers. These standards take as a point of departure problems associated with universal guidance and, in effect, move the accountability for good solutions from the standard setter to the user of the standard. The development of risk- and values-based frameworks as the basis for collection management has been instrumental for the development of these more open-ended standards. There has been a shift away from the precautionary principle to a risk-managed approach (Staniforth 2014).

Taken together, there has been considerable development on the knowledge base for indoor climate control. The current state-of-the-art is based mainly on materials research and the predictive power of computer modelling, ranging from simulations of crack propagation in wood to simulations of future indoor climates. An ambition is to be able to produce rational strategies for indoor climate control, replacing old recommendation which were not sufficiently evidence-based (Bratasz 2013). This development is not paralleled by a consensus about how guidance on indoor climate control should be codified in standards and guidelines, but there is a general trend toward facilitating decision making rather than making decisions on behalf of the end user. The decision-making context where scientific evidence is supposed to be utilized is framed in terms of risk management, and standardization is thought to play a decisive role for transferring scientific knowledge to decision-makers.

3.4. From rules to risk

The following is an attempt to contextualize the development evolution of standards described above. Risk-based frameworks for preventive conservation were developed from the 1990's and onward, with much of the pioneering work made by Waller (1994, 2003), Michalski (1994) and Ashley-Smith (1999). These frameworks systematized collection care to a level not seen before, and provided tools that could be used to effectively allocate the limited resources available for preservation. Waller and Michalski (2005) argued for a "paradigm shift for preventive conservation", consisting of going from a rule-based decision model towards a predictive risk framework. They argue that the lack of an effective feedback mechanism in preventive conservation makes a process-oriented decision approach unproductive, leading to a situation where handbook recommendations have become a proxy for the well-being of collections. With the need to prioritize scarce resources they argue for a decision-model based on predictions of the loss of value to collections.

The Cultural Property Risk Assessment Model (CPRAM) developed by Waller (2003) is an example of a framework for how risks to collections can be quantified in a comprehensive assessment by applying the standard technical definition of risk as the product of probability and consequence. The negative consequence is defined as the loss of (cultural) value over a chosen time period, often suggested to be 100 years for a mixed collection. The idea is to systematically assess the overall magnitude of risk to the collection, defined as the total loss of value over the period. The result of the assessment is supposed to be used as input to a successive step where risks are managed in a resource effective way.

This development of risk-based frameworks for collection care has had a major impact on both the discourses and practices of preventive conservation. Risk has become the lingua franca in training material, policies and, as described above, standards and guidelines. Standardization has moved from being rule- to risk-based, from a focus on outcomes to a focus on processes. A relevant question is why this development has occurred at this particular point in time? Apart from being a part of a general transformation of society as a whole, it can be argued that an increasing professionalization of cultural heritage management, and the demands on rationality resulting from this development provide at least a partial answer.

Heritage conservation became a highly professionalized enterprise during the 20th century (Barthel-Bouchier 2013). A process of rationalization has followed upon this professionalization, with increasing demands on tangible results, responsible allocation of resources and transparency of decisions (Barthel-Bouchier 2013). Jones and Yarrow (2013) discusses how new modes of governance, related to external pressures such as funding schemes and legal frameworks, have shaped conservation practice by demanding accountability, transparency and that interventions are evidence-based.

At the heart of this rational turn of cultural heritage management is the preoccupation with values. Practitioners and academics alike tend to share the position that conservation is to be understood as primarily a values-based activity (Pendlebury 2013). The notion that the cultural significance of a place or an object should guide decision-making is a cornerstone for contemporary theories of conservation (Avrami *et al.* 2000, Muñoz Viñas 2005, Mason 2008, Worthing and Bond 2008). The risk management discourse offers an appealing organizing logic for how values can be systematically incorporated in management decisions.

Discourses about risk have been powerful in transforming the management of uncertainty in organizations: various activities referred to as risk management are advancing in all types of organizations, and at all levels (Power 2007). More and more phenomena in society are characterized as risks (Giddens 1999). The term "risk society", however, points more at a logic for how power is organized and distributed in society than that the world has become a less safe place to live in (Beck 1992). The outcome of uncertain events where in ancient times believed to be in the hands of God, and the concept of risk was invented on the premise of human intervention, bound up with ideas about the ability to foresee and control the future (Bernstein and Boggs 1997, Giddens 1999). It is the ability to organize and control that transform contingency into risks: "when uncertainty is organized it becomes a 'risk' to be managed" (Power 2007, p. 6). With its roots in statistics and calculus, risk management appeals to values of science and rationality (Power 2007), and resonates with modern society's cultural trust in numbers as the primary basis for rational decisions (Porter 1995).

Formal risk management models tend to share a number of underlying assumptions about the nature of risk and the possibilities to control it. Among these assumptions are that risk is considered to be able to measure on a neutral scale, i.e. different risks can be compared, that risk can be calculated as a product of probability and consequence, and that risk management consists of a fixed sequence of rationally ordered distinct steps (Boholm 2010).

Quantitative risk assessments, such as the CPRAM, can be described in terms of complexity, uncertainty and ambiguity (Renn 2008). Risk assessment related to the indoor climate will score high in both complexity and uncertainty for some risks, such as mechanical damage, and be fairly predictable for some risks, such as fading. One reason for the complexity is the diversity of artefacts within most collections when it comes to materials, composition and vulnerability. Muñoz Viñas (2005, p. 125) has argued that every individual historic artefact is unique because of differences in production and historic climate conditions, which make them "escape the realm of scientific predictability". The interactive effect among different deterioration agents, the unknown status of many causal relationships and the long delay period between cause and effect are also contributing to the overall complexity.

Risk management might at the surface seem technical and formal, but risk has always a subjective, value-laden, component (Hansson 2010). However, difficulties invariably arise when attempting to quantify the multifaceted values ascribed to heritage (Mason 2008). Risk assessments for conservation purposes will therefore always be ambiguous undertakings. They are intrinsically ambiguous because of the subjective nature of the values that are attributed to objects. Predicting physical change is not enough, as there is no simple relationship between a change in state and change in value. Damage is, in this case, necessarily a value judgment (Ashley-Smith 1999, Strlič *et al.* 2013). Adding to the ambiguity is the fact that the value of an artefact is realised first when it is used, which implicates that it would be more analytically correct to treat value as accrued benefit over time when using a risk-based framework (Michalski 2008).

Being in some cases complex and uncertain, and always ambiguous, using quantitative risk assessments in this context clearly has limitations, and may end up as "seeking the grail of objectivity in its quantification of factors.“ (Stubbs 2004, p. 287). Despite this, there is probably no other strategy that will give more comprehensive and reliable input to decision-making – I would suggest that the question is not if risk-based frameworks should be used, but how they can be integrated in the complexities of conservation practice, characterized by situations which are at the intersection between different forms of professional expertise (Jones and Yarrow 2013). As Legnér and Geijer (2015) have pointed out, much of the academic work done related to preventive conservation is in essence normative and positivistic. There exists a whole genre of works which outline values- and risk-oriented normative models for how conservation practitioners can transform their work practices to achieve improved results, (e.g. Caple 2000, Keene 2002, Waller 2003, Appelbaum 2007, Worthing and Bond 2008). I would suggest that such normative work, which without doubt is much needed, should be balanced by research that examines how the same normative models are used in practice, and what kind of processes of mediation and translation that are needed to integrate them with existing work practices.

In sum, the development of standards has not been a linear process where accuracy and precision has increased along with the development of scientific knowledge. Rather, there is a great variety in how standards are written, how they are intended to be used and presumably also how they actually are being used in practice. Standards are not neutral ways of condensing scientific evidence, their impact on practice is broader in terms of shaping expectations and ways of framing problems. The impact of standards and guidelines on practice has not been systematically studied and the use of standards remains an under-researched area.

4. Results and discussion

This chapter presents the results of the papers and a discussion of how they relate to previous research. My aim is to integrate the results and show the progression between the papers, i.e. how the papers are linked and build on the results of previous papers. The section is organized around the research aims, starting with the specific aims and ending with how the combination of results contribute to the overall aim of exploring and bridging the science-practice gap. However, I will start with a discussion of the research problem and how it has evolved throughout the thesis work.

4.1. Exploring the science-practice gap: an expansion of the research problem

As described in the introduction, there has been a transition throughout the thesis work in how the science-practice gap has been approached and understood. In the two first papers I try to pinpoint relevant knowledge gaps and expose uncertainties involved in risk assessment. Paper I and paper II are reviews of current knowledge which can be used for risk assessment of the indoor climate in historic buildings. In relation to the aims of thesis, they lay a ground for going further in the analysis of the science-practice gap. In paper III, I try to understand the limitations of using existing knowledge, and especially existing decision support in the form of standards, for risk assessment in a case study of an historic house museum. The results of the case study in paper III explicitly suggests that the bottleneck for improved practice is not to be found in a lack of knowledge about climate-material interactions, but rather in the utilization of existing knowledge. This is also implicitly suggested in paper I and II, and in combination these three papers point at a real and substantial science-practice gap, but gives little guidance on how it could be bridged.

Paper I is a review of the status of knowledge related to mechanical damage to hygroscopic materials in unheated or intermittently heated historic buildings in Sweden. When the risk for biological damage, such as mould growth, is reduced to an acceptable level, then mechanical damage is the crucial risk to manage with indoor climate control. Hence, uncertainty about what conditions that will result in unacceptable mechanical damage is a barrier to low-energy solutions. The paper shows that the research in this area is based on laboratory studies of the mechanical properties of individual materials. There have been relatively few research groups dedicated to the topic and there is not a large amount of published studies. Computer simulations of how individual or composite materials are damaged due to fluctuations are increasingly common. The bulk of research has mimicked a standard museum environment with a temperature range for human comfort. There have been only a few studies on aged artefacts in dynamic, real life environments, and systematic population studies on collections were lacking.[5] Nonetheless, the review showed agreement within the research community that the dominating methodology of using laboratory studies on the mechanical properties of individual materials is a viable method for producing results that have bearing on practical decision-making regarding composite objects, a conclusion supported by a later review on painted wood by Bratasz (2013). Within the practitioner community it is debated how useful the current knowledge is for estimating damage to composite and fragile objects (Bickersteth 2014). There is no consensus among researchers either, e.g. a recent review by Luxford *et al.* (2013), which focuses on veneer and marquetry objects, argues that previous research give limited understanding of the performance of the object as a whole, and call for more research where real display environments are studied.

In paper I it is shown that in the two cases discussed (an unheated historic palace and an intermittently heated rural church), there are considerable knowledge gaps which make risk assessment difficult. There is a lack of knowledge about the influence of low temperatures on the risk for mechanical damage due to fluctuations in RH. There is also a lack of knowledge about the influence of the short-term fluctuations of RH caused by intermittent heating in churches.

Paper II is a review which identifies and qualitatively categorizes the uncertainties involved in producing predictions of future indoor climate risks in historic buildings. The sources of uncertainty involved in such predictions are disaggregated and discussed. Although the paper is covering climate change impacts, the parts about building simulation and damage functions are relevant also for more mundane risk assessments made in relation to decisions about the indoor climate in historic buildings. A conclusion of the paper is that uncer-

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[5] Since the writing of paper I, there has been exploratory studies in that direction e.g. Bylund Melin and Legnér (2014).

tainty management, and especially a probabilistic treatment, is rare. As an example, most damage functions are only described in deterministic terms (Strlič *et al.* 2013).

Closing the knowledge gaps identified in paper I and II, and thereby narrow the uncertainty range for risk assessments, will remain important, but also difficult and resourceful undertakings. Only incremental improvements can be foreseen. A conclusion is therefore that an improved knowledge base for risk assessments will not have a profound impact on practice. Rather, the reviews implicitly suggest that the key for more sustainable management is to make better use of already existing research.

This argument has a parallel in the field of climate change adaptation. There is a demand from decision-makers on scientists to deliver increasingly accurate and precise predictions about the impacts of future climate change, preferably followed by statements of their likelihood (Dessai *et al.* 2009). The inherent uncertainties in such predictions make this a precarious, or even impossible, task (Dessai and Hulme 2004). It has therefore been argued that decision strategies for adaptation should rely on the robustness of decisions, in the sense that adaptation measures should be robust in a wide range of future climates (Wilby and Dessai 2010).

In paper III, it is concluded that the weak link when trying to improve the indoor climate is the difficulty to make risk assessments for an indoor climate that is far from the standard recommendations. In particular, it points at the difficulties of using existing standards and guidelines for improving the indoor climate. To properly interpret and apply standards and guidelines, there is a need for expertise. In the case such expertise is available, standards become more or less redundant as experts rather use the sources directly, i.e. the research frontier. In the many cases where expertise is not available, the users of standards might fail to interpret standards and guidelines in plausible ways. Furthermore, the existing (outcome-oriented, see paper VI) standards fail to address the varying demands which will be specific for each building.

Recent thinking on indoor climate control standards for historic buildings (and collections) which has resulted in process standards such as PAS 198:2010 and EN:15757 is much in line with the argument above, that outcome-oriented standards have drawbacks as they will be overdetermined in relation to specific cases.

The results of the initial three papers (I, II, III) taken together provide an overview of the technical knowledge gaps and the limits of existing technical knowledge in guiding decisions. Although there are substantial knowledge gaps which should be addressed by further research, it seems obvious that something else is missing. Little is known about how knowledge actually is shared and used within this decision-making context. Despite the amount of technical research performed, the production of normative tools and methods for decision-making and the effort put into standardization, it seems to be a largely un-researched area to what extent this new knowledge was used and how it was used in practice. Therefore, I embarked on a new path when trying to explore how decisions actually were made and knowledge was shared. To resume to the discussion about the science-practice gap from the introduction, I attempted to focus more on the role of social processes in the interaction between science and practice.

As a result, I began with the case study in paper IV, where I try to understand how decision processes actually unfold in a historic house museum. The major conclusion from this study was that the decision processes were deviating from what reasonably could be expected from the common account of rational decision-making inscribed in the techno-economic model of technological change. As a consequence, existing decision support, such as indoor climate standards, had not been considered relevant. The typical decision process invisibly inscribed in standards and guidelines, incorporating a distinct and discernible step in which pros and cons are weighed against each other, was in fact missing. Not surprisingly, standards had not played an important role for the evolution of the indoor climate control system.

However, the absence of this taken-for-granted decision process, in which decision-makers constantly are eager to improve the status quo, could not simply be explained in terms of incompetence or irrational individual behaviour. The actors which had an influence on the indoor climate control made plausible judgments based on their experiences and positions. They all seemed to have valid arguments for their individual positions. As an example, there had been considerable side-effects with previous installations of new technology, as well as some new installations in other buildings. Given the acceptable risk associated with the existing system, and the small benefits that could be expected with an improved system, there existed rational arguments for maintaining status quo. However, these arguments had not been obvious for an observer with limited knowledge about the case-specific context, approaching the problem from outside. What this change of perspective implies, is that when studying decision processes from within, the decision situation gets more complex and the borders between science and practice can no longer easily be drawn in the sand. In effect, the judgement whether or not an argument is rational or not becomes contingent of what system level that is considered. If decision-makers have rational arguments for not adopting new technology, then the existence of the science-practice gap, at least in its most basic form, becomes contested. A further discussion of this, as well as the implications for further research, will take place at the end of this chapter.

4.2. Understanding the decision making context

A hypothesis that has shaped the overall research design of this thesis has been that in order to develop effective policies and decision support, there is a need to get a more nuanced understanding of how decision-making unfold in practice. The first specific aim has therefore been to *understand how decisions are made and actions are taken in in the specific context of indoor climate control in historic buildings housing cultural collections*. While papers I-II lay a ground for understanding the technical context for such processes, it is the three last papers, and most substantially paper IV, that bring new results to reach this aim.

The underlying motivation for the case study in paper IV was to get a more thorough understanding of the science-practice gap, and thereby open up for the development of more effective decision support. As a case study, I aimed to select what Flyvbjerg (2006) calls a critical case. Many smaller heritage institutions have difficulties to provide adequate indoor climate control for their collections, due to a lack of competence and funding, but also because preventive conservation is not considered important in relation to other objectives. I therefore wanted to study how decisions were made in an organization where preservation was in focus, and where competence and resources were not lacking. The historic house museum was chosen partly because there were ample financial resources and the availability of professional expertise did not seem to be limiting factor, partly because there were many conflicting objectives related to the indoor climate. In choosing such a critical case, I aimed to understand not just the case-specific symptoms, but the deeper causes to why finding an *indoor climate compromise* emerges as such a challenging problem in many historic buildings.

The results of paper IV become salient only when projected on the background of the traditional account of strategic decision-making. This account, commonly taken for granted by both researchers and practitioners, comprises a specific interpretation of the anatomy of decisions as well as the relationship to choice, determination and action (Hendry 2000). Decisions are regarded as conceptually unproblematic and thought to follow the consequential logic suggested by normative decision theory. In the introduction it was discussed how common interpretations of the science-practice gap are centred on models of change which consider rational choice as the basis for action. Such interpretations are closely linked with the linear model of knowledge transfer, and in effect the techno-economic model of technological change which has been described as dominating the energy policy discourse (Guy and Shove 2000, Lutzenhiser 2014).

The objective of paper IV was to illustrate how the interaction between perceptions and experiences of different professional groups are pivotal factors for the management of the indoor climate in heritage buildings. The indoor climate control strategy that had evolved at the historic house museums had been essentially the same for a long period of time; it could be considered a stable practice. To understand why such stability occurs and how it is sustained is essential for how, and to what extent, changes towards more environmentally sustainable indoor climate control strategies can be achieved. The case study revealed a lack of decisions per se, and it became evident that the current stable practice was more a product of an historical unfolding of events than the outcome of rational aspirations. Most of these events had been of coincidental nature, and frequently it had been unexpected events that had caused a change, rather than strategic thinking.

The practices concerning indoor climate control had emerged and stabilized in the absence of a rational decision process comprising the identification and evaluation of alternatives. Instead of decision process per se, there was on-going negotiation about indoor climate control where each actor took a unique position based on experience and pre-understanding. The study illustrates how discussions among and between social actors, as well as the way their respective priorities are negotiated, are essential features of the actual management procedure and have a strong impact on the ability to modify it. Instead of explicit decisions there were negotiations taking place about the indoor climate, sometimes resulting in action. Thus, what was going on is better understood as "issue streams", a construct proposed by Langley *et al.* (1995) for understanding decision-making in organizations. Issue streams are on-going discussions which at times result in action, but not necessarily due to identifiable decisions. Multiple issue streams form a complex process which is situated in the specific organizational context. The discussions of the indoor climate taking place at the museum related mainly to issues about preservation and thermal comfort. These parallel and sometimes intersecting "issue streams" were in turn constituted by earlier decisions, controversies and attempts to improve the indoor climate.

The responsibilities for the building, the collection and the human beings within it were distributed among a number of organizations. Each organization was represented by individuals with specific professional backgrounds, and with specific responsibilities and priorities with respect to competing objectives regarding the indoor climate. Several actors had stakes in relation to indoor climate control; it was the locus of competing objectives, which in the case of thermal comfort had resulted in a never settled controversy. However, despite the many competing objectives, there were on an overarching level consensus that preservation was the dominant rationale for indoor climate control, and it therefore had a hegemonic position. This varying degree of priority among the main rationales for climate control could be described as a hierarchy, with *preservation* at the top, *energy* at the bottom, and *comfort* somewhere in between. All actors seemed to share this basic horizon of perception, framing their expectations for what was considered possible to achieve and decide upon. The difficulty to reach consensual compromises in ways which did not conflict with the overarching objective of preservation was decisive for the maintenance of status quo. One effect of this was that neither energy saving, nor thermal comfort, were discussed in explicit or formalised ways.

The level of acceptable risk was a crucial feature of this discourse, in the sense that as long as the criterion for what was considered acceptable risk was fulfilled, changes were considered unnecessary. This actually hampered a change of practice, leading to only rare and minor adjustments of the existing technology for climate control. It is interesting to notice how the level of acceptable risk was situated, bound up with the specific social and material context. This situated level was shared among different professionals despite the fact that some of them worked in other contexts where acceptable risk was defined differently.

Adams *et al.* (2014) showed how the institutional context is important for framing the negotiations between various forms of professional expertise that are central for heritage management. The results of paper IV emphasize the importance of the institutional context by exposing how it shapes the interplay between different professionals. This implies that a viable way to improve the indoor climate in historic buildings is to support decision making that pay attention to institutional contexts, as well as the case-specific perspectives and interests of the involved actors.

Decision processes related to the *indoor climate compromise* are also one of the focal points of paper VI, but they are studied from a different perspective than in paper IV. Instead of studying a specific process, I try to zoom out one level and focus on the organizational context in which decision processes take place. The indoor climate management of Swedish churches was chosen as an object of study due to the central role energy and indoor climate issues. The management of Swedish churches is still highly decentralised despite the tremendous challenge to balance use and preservation on a tight budget. Individual parishes are responsible for their own churches, and the decision-making regarding renovation is often made by laymen. However, all alterations require consent from the County board, which means that heritage professionals are involved in e.g. new installations of heating systems.

A result of paper VI was the identification of a division between continuous daily management and more infrequent projects that were relevant for indoor climate control, e.g. installation of new heating systems. The decentralized structure and the division between daily management and one-shot knowledge intensive projects made it difficult to systematically use feedback for continuous improvement and knowledge sharing. There were weak links between the permanent organization responsible for daily management and the temporary organization that emerges in connection with renovation projects. This resulted in problems with knowledge sharing within the organization as a whole. In connection with this, a lack of evaluation and feedback regarding indoor climate control was evident at both the level of individual churches, as well as on aggregated levels.

A result which perhaps is not surprising, but highly relevant for this thesis as a whole, is the limited role standards and guidelines generally have had for decisions about the indoor climate in Swedish churches. Standards and guidelines have not been considered applicable, either by being too generic or too specific. Users have not been able to interpret and translate them to fit the varying prerequisites of individual churches. Interestingly, there is often a locally established, informal way of determining e.g. service temperature or heating system.

A synthesis of the results from paper IV and VI is that we see a lack of the clearly identifiable situations of choice which I have argued are taken for granted in the scientific discourse. The decisive events where experts, decision-makers and stakeholders gather and evaluate the pros and cons of different alternatives are simply not there. The complex and largely unstructured management processes that have resulted in action have not offered the necessary moments where standards and guidelines could be accommodated. An implication of this is that the development of decision support, as conceptualized in the scientific discourse, to some extent is based on shifting sands. Rather than keeping the complexity and disorganisation of actual decision-making at arm's length, I suggest that it could be used to underpin the development of decision support. Broadly, these findings about unstructured decision processes are supported by studies of decision-making in organisations. The rational account of how decisions come about has been shown to underestimate the ambiguity, confusion and complexity involved in actual decision-making in organisations (March 1994).

By looking at indoor climate control as the result of a long-term management process, intertwined with other aspects of management, it becomes evident that indoor climate issues are affected by and affect broader issues which relate to other aspects of management of historic buildings. There is therefore a need to acknowledge the significance of indoor climate control for sustainable management by involving a wider set of decision-makers and stakeholders. In parallel, to achieve strategic improvement a wider set of performance indicators must be used for feedback - monitoring the indoor climate is not sufficient.

In the introduction of this thesis it was implicit how scientific knowledge about deterioration had exerted only minimal influence on previous decisions about the indoor climate in Skokloster castle. Instead, ideas about traditional ways of doing things – we can call it an intuitive approach – had been decisive. I would argue that this stance of the managers were not because of ignorance, but a result of conscious considerations of the validity of scientific knowledge versus personal experience. Recently, partly due to accumulated climate-induced deterioration, partly due to conservators trained in preventive conservation gaining more influence, there has been a clash between this intuitive approach and the allegedly rational approach based on scientific evidence. Such a tension between intuitive and rational modes of thinking is also discernible in the case study in paper IV. To what extent this is a common phenomenon in the management of cultural heritage remains to be investigated.

4.3. The management of uncertainty

The second aim of the thesis is to explore and discuss how uncertainty relating to decisions about the indoor climate can be managed and communicated to support adaptation of historic buildings. Uncertainty pervades all decision-making, but in this context it is especially relevant for the assessment needed to determine acceptable levels of risk due to climate-induced deterioration.

Paper II is a review of the uncertainties that have to be managed when producing risk maps of climate change impacts of indoor climate related risks in buildings. It contains a categorization of the sources of uncertainty in risk maps (table 1). Uncertainty always originates from a lack of knowledge, however it is often useful to distinguish between epistemic and aleatory uncertainty. Epistemic uncertainty can be reduced with better knowledge while aleatory uncertainty stems from randomness in nature and cannot be reduced; it is a property of the phenomenon being studied. In paper II, a third type of uncertainty is used in the categorization: ambiguity. Ambigu-

Modelling step	**Major source of uncertainty**	**Dominating nature of uncertainty**
Forcing conditions	Socio-economic pathways	Ambiguity, epistemic
Climate models	Model deficiencies	Epistemic
Internal variability	Randomness in nature	Aleatory, epistemic
Building simulations	Specification	Epistemic
	Model	Epistemic
	Scenario	Ambiguity, epistemic
Damage functions	Input	Epistemic
	Deficiencies of the function	Epistemic, aleatory
	Interpretation	Ambiguity

Table 1. The major sources of uncertainty in risk maps (paper II).

ity results from the presence of multiple ways of understanding or interpreting a system and is a type of uncertainty which arguably is relevant when making risk assessments of cultural heritage, as the interpretation of risk is contingent on values.

The gold standard in climate change impact assessment is to quantitatively describe the uncertainties in each modelling step, with the ambition to produce risk information with a known uncertainty range described in terms of a probability density function (Wesselink *et al.* 2014). However, only few studies of the effect of climate change on buildings have set out to pursue such an ambitious approach (Wilde and Tian 2011). Complexity as well as the difficulties to assign probabilities are the reasons for this. There is disagreement if assigning probabilities of the socio-economic pathways that make up the forcing scenarios make sense at all. The forcing scenarios aim to represent different possible future trajectories. It has been argued that some of these scenarios are more likely than others, which implicates an assignment of subjective probability (Schneider and Kuntz-Duriseti 2002, p. 68). There is also disagreement to what extent a probabilistic approach is relevant for the uncertainty produced in climate modelling, as different climate models might have the same systematic errors (Parker 2010, Frigg *et al.* 2013). Furthermore, there will always be an unquantifiable range adding to the total level of uncertainty in climate modelling, due to so called unknown unknowns (Jones 2000).

In paper II it is shown that for the type of risk information that is reviewed, it is not possible to come close to a probabilistic approach to uncertainty with the current state of knowledge. This is problematic, as an unknown level of uncertainty in the end result makes the information difficult to use. Still, given that state-of-the-art models are used in every step, it will give valuable information for policy making. Even if the uncertainty range is unknown, the method to produce risk maps can be used for parameter studies in order to compare different future scenarios and different risks.

The "best guess" approach commonly used for climate change impact assessment (Schneider and Kuntz-Duriseti 2002, p. 68) and the "worst case-scenario" approach commonly used for heritage damage functions (e.g. Bratasz 2013) are problematic as the results of risk assessments based on these approaches risk being wrongly interpreted by decision-makers. With a "best-guess" approach the decision-maker might interpret the information as representing the most likely future scenario. By using a worst-case scenario the risk of damage might be exaggerated which is problematic in a risk management context (Paté-Cornell 1996).

With the exception of the uncertainties related to climate change, the findings in paper II have wider applications. Predicting the effect of control on the microclimate always (although often implicitly) involves some kind of hygrothermal model of the building, and estimating the various risks resulting from the predicted indoor climate requires the use of damage functions. Hence, the discussion of uncertainty related to these two steps is applicable for all decisions on indoor climate control. A conclusion of the review in paper II is therefore that there is a potential to improve the management of uncertainty, as both building simulations and damage functions commonly are used in a deterministic way, i.e. the output is not described in probabilistic terms or even as a range. E.g. the stochastic character of mould growth encourages the use of probabilistic methods for modelling mould safety in buildings (Pietrzyk 2015).

The lack of known uncertainty in damage functions (regarding the effects of the indoor climate on artefacts) is an important aspect of the risk analysis made in paper III. The indoor climate in Skokloster castle with regard to the fluctuations and levels of T and RH is far off what is considered safe in standards and guidelines. A challenge with the risk assessment based on this "beyond safe" indoor climate was the difficulty to estimate the change of the magnitude of the risk with a given change of the indoor climate. This challenge was inevitably the weak link for making decisions aiming for optimality. What could be suggested was what direction of change that would be beneficial.

Paper V sets out to empirically test some of the issues about uncertainty management laid bare in paper II. There is a demand from policy-makers and adaptation practitioners for more detailed and refined predictions about climate change impacts to cultural heritage, and a scientific community keen to supply this demand. However, as shown in paper II, the output of climate change impact studies is highly uncertain, although it is often presented in deterministic ways. Thus, paper V attempts to understand how heritage practitioners make sense of generic, ambiguous and complex climate risk information, in this case risk maps from the Climate for Culture (CfC) project. The method used is to present risk maps to adaptation decision-makers in the Church of Sweden and ask how they interpret the maps. It is a qualitative study aiming to understand how the different individuals make sense of the risk information.

The results of paper V emphasized two important lessons for risk communication: first, risk is not a uniform concept; it can be conceptualized in many different ways and tend to be understood differently on either side of the science-practice divide. It was apparent that the notion of risk varied between individuals, rendering the comparison of risk assessments problematic. The fact that the risk information used in the study was presented in a deterministic way (without any indication of likelihood) was not perceived as a major constraint for performing risk assessments. Despite multiple definitions of risk simultaneously in use, interviewees did not seem to have difficulties to elaborate on the information. This supports the idea that understandings of risk are contextual and fluid. Slovic (1998) has proposed that risk can be characterized by a number of attributes in one context, and another number of attributes in another context. None of these attributes are essential; hence, there is no universal way of defining risk. Second, the importance of uncertainty, being a crucial feature of risk, was downplayed in the sense-making process. It turned out that uncertainty was not considered an issue: it was the overall impression of the information as being salient and credible that dominated how the information was perceived.

The major conclusion of paper V is that the results from CfC (and similar projects) are likely to be interpreted in misleading ways if the acts of interpretation and assessment are bluntly handed over to end-users. The dissemination of risk information, also from projects which at the outset have aimed at producing knowledge relevant for end-users, must be both customized and tested for specific target audiences in collaborative efforts by stakeholders and scientists. Paper V provides a new methodology for performing parts of this process.

A more fundamental conclusion is that that how risk is understood is embedded in the institutional and organizational context. Boholm *et al.* (2011, p. 3) have argued that conceptions of risk "are inseparable from the mixed influences of the contexts in which they emerge, are communicated, and shared". In this case, it was apparent how the interviewees tried to make sense of the risk information by using the organizational context as a frame of reference, e.g. by referring to existing organizational routines, previous experiences as well as organizational structures available for controlling the risks.

4.4. Standards and guidelines

The final specific aim of the thesis is to explore and discuss how decision processes regarding indoor climate control can be supported with standards and guidelines to achieve a more sustainable management. Paper III, IV and VI all explore the limitations of current standards and guidelines in various ways. Paper III shows shortcomings in current standards regarding their usefulness for informing risk assessment at a historic house museum where the indoor climate is well beyond what is considered a normal museum indoor climate. Paper IV and VI shows how standards might not be used as intended by standard makers, or not used at all. Finally, paper VI draws on the results of the previous papers in an attempt to suggest ways forward for standardization of the indoor climate in Swedish churches.

As a precursor to the specific results of the papers, I will start with discussing the more general dilemmas of standardization, mainly by drawing on the work made by Timmermans (2010) and Brunsson and Jacobsson (2000). Two fundamental questions are: what are standards, and what are they good for? The general answer to the latter question is that standards provide answers to common problems. The wheel does not have to be invented again and again. At the surface, standards might seem to provide neutral advice on how to solve primarily technical matters. However, standardization has wider implications and standards are rarely as neutral as often conceived. For example, standards can bring resolution to debates that might encompass different social meanings of a technology (Pinch 2008). Standardization is not void of value judgments: standard makers have to negotiate a range of subjective issues such as choosing between contested scientific evidence and what level of risk that is deemed acceptable (Timmermans and Epstein 2010). Standards can also have other purposes than providing answers to common problems. They are embedded with professional expertise and can be used to sanction actions by providing authority to the user (Brunsson and Jacobsson 2000). Standards are often understood as being primarily static phenomena, resulting in stabilization and convergence of processes. However, there is more dynamics in standardization than generally believed (Brunsson *et al.* 2012). Standards and practices tend to co-evolve. There is no clear-cut line separating the domain of standards from that of conventions, and these two often reinforce each other in practice (Timmermans and Epstein 2010). Brunsson (2000) calls standardization a form of soft law operating in-between norms and legal order.

A low carbon future will demand better adaptation of historic buildings to the local climatic conditions, both regarding their use and the technology used for indoor climate control. Thus there will be a need for customized solutions that are adapted to local conditions. On the other hand standardization has an inherent tendency to push development in the opposite direction: toward universality across cultures, time and geography (Timmermans and Epstein 2010). This fundamental challenge for standardization originates in the simple fact that a standard is general whereas practice is specific. It does not, however, have to be a contradiction between flexibility and standardization: good standards allow for deviation and improvisation (Timmermans and Berg 2003). Few standards work as intended by the designers of standards, and most standards are "tinkered with", whether slightly or fundamentally (Timmermans and Epstein 2010, p. 81).

In general, standards can be defined as either *outcome standards* or *process standards*, where the former require the user to deliver a certain outcome, and the latter is intended for standardizing organizational processes (Brunsson *et al.* 2012). The effect of adopting a process standard is, due to its flexibility, in general more uncertain than the effect of adopting an outcome standard. Process standards are therefore increasingly linked to outcome standards (Brunsson *et al.* 2012). A recurring argument in this thesis is that the traditional, outcome-oriented standard, used for indoor climate control is difficult to apply in practice. In paper III, it becomes obvious that current outcome standards are unable to guide the user about the risk of deviating from the suggested "safe zones". Managers of historic buildings will value the different objectives of the *indoor climate compromise* in different ways, and outcome standards suggesting generic, fixed numbers have difficulties to support the customized solutions that are needed. The notion that universal guidance is problematic, especially for historic buildings, is not new. In paper VI, it is argued that there is not only a mere technical explanation for this, but also a social one: the ways buildings and collections are used and valued have major implications for what technical arrangements that are chosen. Outcome standards incorporate value judgements, such as the setting of acceptable thresholds, which might be concealed for the user of the standard.

In the case study made in paper IV, it was evident that there was a lack of decisions per se, and hence standards did not play an important role for the management of the indoor climate: they were not used. Again, this puts the finger at a problem with existing standards and guidelines: who is supposed to be the user? When are standards supposed to be used? Existing standards and guidelines (with an important exception in PAS 198:2010) do not explicitly address such issues, and a management perspective is generally lacking. This result is supported by the results in paper VI, where it is obvious how there is a decoupling between the one-shot, project-based, process in which indoor climate control systems are designed and implemented, and the long-term management process where systems are operated, maintained and tuned. In sum, the results of paper IV and paper VI shows the need for decision support which take such management issues into account, i.e. it is a strong support for the development of process standards, which aim to substitute or improve unsystematic decision-processes, as well as merges the decoupled processes regarding design and implementation on one hand and operation on the other hand.

In paper VI, the recent development of standards for indoor climate control is reviewed. The review shows that standards have multiple forms and multiple ways of intended use. There is a basic dilemma for standards makers that end users expect general and clear cut advice, whereas the complexity of the problem requires individual solutions based on risk assessment and negotiation of objectives. To resolve this, standards have evolved from simple prescriptions of universal specifications to become more sophisticated, informative and flexible. However, the lack of testing and evaluation of how standards are used suggests that this development emerges mostly from a lack of success with former approaches.

The review also points out how the scope of standards is shifting: outcome standards are replaced by process standards. To become useful, process standards have to be complemented with both expert knowledge and value judgements. They require more resources to be implemented than outcome standards but promise improved end-results. However, if the organization adopting the standard lack the resources needed for a successful use of a process standard, it might not lead to improvements.

In paper VI there is a discussion of the relationship between type of decision logic and the type of standard. The decision logic implicit in standards is generally rule-based, as standards typically offer rules for situations of choice (Brunsson and Jacobsson 2000). The type of decision logic that is invoked by such rules is one of identification. First, the situation at hand is identified; second, the appropriate rule is identified. Such reasoning is not about calculating consequences. The judgment needed deals with identifying situations, identities and rules (March 1994). Such processes of matching rules and situations are often routinized within organizations (Berkhout *et al.* 2006). As a result, many and strong rules within an organization diminishes the need for decision-making (Brunsson 2007).

Process standards take a different route and encourage consequential logic: the decision is framed as a matter of optimizing costs and benefits. Such consequential logic resonates with the contemporary emphasis on quantitative risk assessment as a foundation of conservation decisions discussed earlier, as well as the increased demand on conservation decisions to be transparent and evidence-based (Jones and Yarrow 2013).There are, however, reasons to be cautious as practitioners might be reluctant to use formalized decision frameworks. Risk management in organizations tends to be intuitive and experience based, despite efforts to formalize it (Boholm 2010). If guidelines do not resonate with existing, practical ways of managing risks, there is a risk that they will not be used at all (Boholm 2010). Experiences from the construction sector show how practitioners base their decisions on previous experience and current practice rather than formal decision tools and management control systems (Gluch 2005). These experiences suggest that the key question is if standards which require risk-based decision making are powerful and usable enough to rectify existing decision processes to the extent that informed risk/benefit trade-offs will substitute local conventions and simple rules.

Several suggestions for how standards could be improved to address the identified problems are given in paper VI. These are based on the inquiry of Swedish churches, but they have bearing also on other types of buildings or management organizations.

An overarching result is that standard makers and users of standards should embrace the idea that standards with different scopes can be used in parallel to serve different purposes at different levels of abstraction, an idea in line with what was proposed by (van Gigch *et al.* 1996). At the top level there can be management standards that define processes, duties and roles for the long term management. The decision process to come up with target specifications and technical solutions could be the scope of another standard. Outcome standards focusing on various damage functions could be used as decision support tools, complementing other sources of risk information.

Finally, there will probably always be a demand for standards and guidelines that give simple and universally applicable advice when possible. I suggest that there is a need for all these kinds of standards; the question is when and how to use them. The idea of such a landscape of standards opens up for the individual standard to be more specific about its scope and its intended use, and thereby becoming more focused.

As pointed out earlier there is a risk for a decoupling between the decision and implementation phase, and the following operating phase. In order to integrate these two kinds of processes and close the feedback loops in-between them, I suggest that the management of the indoor climate should focus more on feedback at the overall *system level*. Today, feedback is primarily used at the *operational level*: it is used to check whether the indoor climate within specified boundaries, whether climate control systems work properly etc. In order to achieve a strategic improvement at the system level there is a need to use feedback of the parameters that are affected by indoor climate control. The main feedback loops at the system level are about preservation, use and resource use. Inevitably, it is more difficult to identify performance indicators for these parameters. Still, this is something that more or less explicitly is done in the design phase. Improvement at both operational and system levels and their respective feedback loops are illustrated in figure 3. I suggest that the importance of improvements at the system level should be acknowledged and supported by standards and guidelines, which today are overly focused on the decision-making needed for the implementation process.

There is an additional level on which feedback can be differentiated, namely depending on if the feedback is used for external observers or for internal use. Timmermans and Berg (2003) argue that the *measuring for judgment* (by external observers) which is nurtured by contemporary management ideals leads to defensive actions by professionals, while the *measurement for improvement*, in which professionals measure and reflect on their own work processes, leads to improved overall results. In figure 3, the feedback loops are intended for internal use, i.e. not for judgment by external observers. The evaluation procedure at the system level requires more competence than at the operational level, which means that there still is a need for external experts in this evaluation.

Lastly, there is a potential to use process standards as a means to produce *local guidelines*, which are applicable for a set of buildings which are similar in construction, use and geographic location. This simple solution could help to overcome the problem that process standards are time and resource demanding in their implementation. In reality such local guidelines are already developed, however often in the shape of a local praxis, which is not formalized or systematically evaluated. This approach would overcome some of the problems associated with the production of individual recommendations for each building which seems to be utopic given the limited resources of most historic buildings.

4.5. Exploring and bridging the gap

In this final discussion I try to draw on the results presented earlier in a broader way. How can they contribute to the overall aim of the thesis, to *explore and bridge the gap between research and practice regarding energy efficient indoor climate control in historic buildings*? How do they relate to previous research?

Qualitative social sciences bring, according to Jasanoff and Wynne (1998), powerful tools for increasing the understanding of how society can deal with the issue of climate change: critical enquiry can show how problems and controversies are framed; how risks are identified and managed; how knowledge is produced and shared in specific, local settings. There is a growing field of critical heritage studies but so far the main focus for this field has been to engage in fundamental questions about the uses of heritage, exemplified by issues of power, diversity and cosmopolitanism (Smith 2012). As argued throughout the thesis, there have been relatively few scholars engaged in such enquiry of conservation practice that fulfils the expectations posed by Jasanoff and Wynne. Critical enquiry of the ethnographic

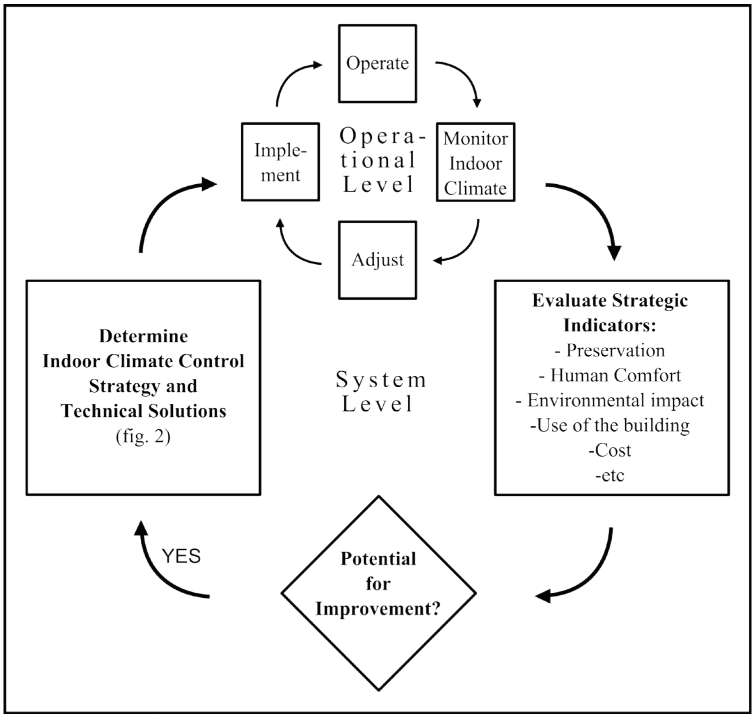

Figure 3. A model for how the management of the indoor climate in historic buildings can be differentiated between operational and system levels.

complexities of the practices of heritage science is lacking, instead there has been a dominance of normative work which ultimately aims to make management more rational. The results presented in this thesis provide preliminary insights into some of the issues raised, by exploring the interface between science and practice.

The introduction of the thesis presented different perspectives on the existence and nature of gaps between science and practice, between what should be done and what actually is being done. Given the results of the papers, is there anything that can be added to this discussion? In a concrete way, the case study in paper IV reveals how the perspective of the observer determines the very existence of a gap and how it can be understood. The notion of an "energy efficiency gap" is bound up with ideas of agency and perceptions of "end users" as responsible agents who tries to make the use of energy as efficient as possible. In the heritage management practices studied in this thesis, it is often difficult to pin down who this end user is. Conserving energy is a peripheral issue for practitioners involved in heritage management, and decisions about energy and indoor climate control are rarely framed as matters of optimization. In addition, the scientific knowledge produced by researchers will not become usable if the individual who acknowledges it cannot incorporate it into work processes that he or she exerts influence over.

It is both common and convenient to perceive end-users as generic heritage "policy-makers" or "decision-makers" responsible for incorporating new knowledge into action. These are proxies for a diverse group of professionals: managers, architects, conservators, archaeologists, engineers, etc. Heritage management is an arena for professional expertise where the power relations and work processes often vary on a case-to-case basis, and where sustainability issues are dependent on negotiations between different professional groups. It is therefore crucial to pay more attention to the specific social and material contexts when trying to understand how knowledge is shared and how it might have an impact on practice.

An important issue which is not yet discussed in the present thesis is the importance of training and education for professionals involved in energy-related decisions in historic buildings. As previously said, energy efficiency is not a major aim for any of the professional groups working with historic buildings. Ryghaug (2003) identified the same problem among architects, arguing that architects are unable to define energy efficiency on the inside of their professional boundary, and that energy efficiency has to be domesticated by the profession in order to change its role in building projects. I suggest that it is important that professionals involved in the management of historic buildings are able to step forward and take the lead role regarding energy- and indoor climate-related issues. These issues play an essential role for long-term management and should not be left to a "decision-vacuum", where it is unclear who is accountable and responsible. A prerequisite for this to be realised is proper training: to take the lead role requires a sufficient knowledge base and an understanding of the issues at stake.

The complexity, uncertainty and ambiguity inherent in much of the knowledge that professionals are supposed to draw on in decisions about the indoor climate make it impossible to draw distinct borders between what could and should be done, hence the size of a gap between science and practice will remain contested no matter the perspective of the observer. In contrast to the unclear status of a gap between science and practice, there is a perhaps more interesting and tangible gap between scientific discourse and actual practice. The qualitative studies in the present thesis reveal a mismatch between discourse and practice concerning indoor climate control. This is illustrated by the two following quotes:

> The process of designing a new or altering an existing heating system shall be carried out by a multidisciplinary team in close consultation with the users of the building. The team shall include all relevant expertise, including those professionally qualified in the conservation of structures and, heritage items and in all other relevant technical aspects involved. (EN 15759-1)

> There is a lot of incompetence in for example parish councils. They are trustees and are supposed to decide in issues ranging from choral music to heating systems, and of course they are lacking competence for all this. In those cases when it works well it is often mere happenstance: an engaged and competent individual happens to be there at the right moment in time. (building conservator, unpublished quote from the study made in paper VI)

The heritage science discourse , here represented by the European standard 15759-1 on heating of churches, is here contrasted with how management processes actually can turn out in practice, represented by the interview quote where a building conservator describes the situation in some churches. The European standard outlines a systematic design process in which relevant expert knowledge is utilized. The discrepancy to the situation described by the building conservator is striking. For example, the ambition to include all relevant expertise in the design process is far off what can be considered reasonable for this case. There is, however, no immediate reason to be worried over this state of affairs. The European standard is not supposed to be descriptive, it is a normative document. What the results of this thesis have revealed is that there is a potential for a more reflexive inquiry that can complement such normative work. Otherwise there is a risk that standards, management models, decision support tools and other normative instruments will live a life on their own, separated from the practices they try to influence.

Apart from the risk of producing documents that remain unused, there are more subtle processes taking place. The way we think and talk about things has an impact on practice in the long run. I would argue that the necessary categorizations, limitations, simplifications in standards can entrench ways of framing problems and have a long-lasting impact. To be able to describe a generic decision process there is a need to focus on the core aspects of the process. The decision context must be kept within manageable boundaries, and certain concepts or relationships have to be defined in a way that limits the complexity of actual practice. In standards and guidelines this is often done through categorization. An example is the various types of historic buildings discussed in this thesis. In discourse, there is a separation between "top-class" museums, historic house museums, historic churches, etc. Standards and guidelines give recommendations based on a typology of historic buildings, uses etc. In practice, however, such distinctions are less clear.

A strong tendency in formal frameworks for indoor climate control is to use a risk-based approach to find rational measures and allocate resources in a cost-effective way. As argued in paper VI, this shift is linked to a change of decision logic and the role of professional expertise in decision-making. By going from a rule-based logic to a consequence-based logic risk assessment is invoked as the neutral tool to inform decisions. The primary role of professional expertise shifts accordingly, and is now considered useful for estimating the impact of different courses of action, rather than for making judgments based on a hierarchy of rules. While, again, I think it is irrelevant to judge whether this development is desirable or not, I believe that there are considerable limits to such "rational" approaches, which both scholars and practitioners should be made aware of.

First, science itself is to uncertain, complex and ambiguous to govern decisions. At times there are low-hanging fruits where science alone can determine the most benevolent way forward. In the case of nature conservation, unambiguously dangerous environmental and health risks led to widespread support of science-based management in the beginning (Gregory *et al.* 2006). However, situations where such uncontroversial thresholds exists have become rare, and the decision to act upon a risk is in the majority of cases a matter of the level of accepted risk and trade-offs between values (Gregory *et al.* 2006). Paper IV showed how the prioritization between different competing objectives, and the local perception of what level of risk that was considered acceptable were powerful in framing what was considered possible and not.

While risk-based frameworks are not a panacea, they provide a potentially powerful way of tackling the complex problem of indoor climate control. Their success in transforming practice to become more sustainable relies on more fundamental shifts related to discourses, risk interpretations and rationales. Risk is bound up in people's understandings of themselves and their lifeworlds (Granderson 2014) and risk has practical, social and political dimensions far beyond what is considered in positivistic risk management (Boholm 2010). Understandings of what is necessary and acceptable are part of an evolving discourse, where not least policy-makers and institutions are active in the shaping and reproduction of ideas (Walker *et al.* 2014).

5. Concluding remarks and future research

Returning to the overall aims, the results of the thesis contribute to an expanded problem definition and to a better understanding of the gap between research and practice regarding energy efficient indoor climate control in historic buildings. While papers I-III outline the background needed for a technical understanding of the involved matters, it is mainly the three final papers (IV-VI) that contribute to a more nuanced understanding of the science-practice gap. The results of these papers point toward a need for a redefinition of the problem. Scientific knowledge alone will not be able to guide the transition to a sustainable, low carbon future; technical research has to be complemented with reflexive research approaches that explore the actual practices of heritage management.

While all papers contribute in different ways to a deeper understanding of how decisions are made and actions are taken regarding the management of the indoor climate in historic buildings, it is in particular explored in papers IV and VI. These papers show how a study of the specific social and material contexts is crucial for understanding how change can come about.

Papers II and V explore some of the difficulties that arise when uncertain scientific knowledge is supposed to inform decisions related to indoor climate control. A conclusion is that while it will remain important to reduce uncertainties, it is of little use in doing so if not more attention is given to how residual uncertainties can be managed and communicated in better ways.

Finally in paper VI, which builds on and synthesizes the previous papers in the thesis, it is suggested how decision processes regarding indoor climate control can be supported with improved standards to facilitate a more sustainable management.

In addition to the results discussed above, the present thesis should have implications for further research. Dillon *et al.* (2014) discuss a "rigor-relevance gap" in heritage science. There are demands on science from two opposing directions. First, it has to live up to the academic rigor distinguishing traditional disciplinary science, second, it is supposed to be relevant for solving problems in society. To achieve the latter there is a standard recipe consisting of more interaction between researchers and policy-makers/practitioners, involving stakeholders in research design, and putting more effort in dissemination of research results (Owens *et al.* 2006). In the words of McNie (2013):

> The process of linking the production and supply of climate-science information with users' demands is a complex, highly contextual social process that requires ample resources and time management, research agendas that are "end to end" and can respond to changing contexts, and organizational commitment to support "use-inspired" research.

Efforts of such co-production, aiming to close the rigor-relevance gap, both risk to be accused of lacking academic rigor and require more resources than standard, disciplinary research. As Spreng (2014) points out, it is often the methodological sophistication that legitimizes disciplinary research. Transdisciplinary approaches are unable to compete in that respect, but might potentially bring the novelty and relevancy that is asked for. However, the research must not be so tailored to user requirements that it loses its critical edge (Owens *et al.* 2006). This is not only relevant for the social sciences and humanities, but also for natural sciences. My conclusion of paper III and V, is that aspects of uncertainty were downplayed in the modelling processes of the Climate for Culture-project to the extent that the methodology lost some of its legitimacy. With a message that is so contested by the general public, it is essential that the underlying research is perceived as legitimate. I would therefore suggest that further research either should have as its primary focus on trying to reduce uncertainties, or engage with end-users in transdisciplinary approaches when the resources and engagement are available to go all the way. Doing something in-between might delegitimize the results of the specific research project in the eyes of the end-users, and in the long run question the scientific enterprise.

The case study of paper IV, the methodology developed in paper V and the normative approach taken in paper VI are all exploring new arenas for research which has the potential to answer some of the fundamental questions raised by Jasanoff and Wynne above, as well as giving guidance on how to proceed in the specific cases that are being researched. I would therefore suggest, in accordance with Jones *et al.* (2013, p. 6) that further studies are needed that focus on how the "complexity of the practices involved in heritage conservation /…/, in particular with respect to how different forms of expertise and skill coalesce to produce specific material interventions". Apart from being capable of raising our understanding of heritage and conservation practice as such, such studies will be useful for informing policy and for educating professionals about the complexities of the problems found in conservation practice.

This thesis has provided a broader and better understanding of the relationship between science and practice regarding indoor climate control in historic buildings. Except of the scholarly value, I hope that the arguments made in the thesis are relevant to a broad range of professionals involved in the management of built heritage, such as architects, engineers, policy-makers, managers, conservators and energy experts, and that these professionals together with researchers in the field will take the discussion further about how a transition to more sustainable practices actually can be achieved. In some way, there will always be a gap between science and practice, and the aim cannot be to fully close it. But we must aim to better understand and navigate this gap in order to facilitate a sustainable management of historic buildings.

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PAPERS

Paper I.

Preventive conservation climate in historic buildings – some gaps in the knowledge

Gustaf Leijonhufvud and Charlotta Bylund-Melin

This paper has been translated from Swedish and was originally published in the Scandinavian journal *Meddelser om konservering* no 1 2009, s. 22-30 with the title “Bevarandeklimat i historiska byggnader - några kunskapsluckor.”

Abstract

The indoor climate in a number of Scandinavian historic buildings such as churches, castles and manor houses often differs markedly from indoor climate recommendations given for museums. Nonetheless, many of these buildings accommodate fragile and valuable objects and interiors. A brief review of the literature on the risk of mechanical damage to works of art caused by fluctuations in temperature and relative humidity is given. Two case studies are presented to illustrate the problem of indoor climates that deviate from common standards. The first is that of an intermittently heated church in northern Sweden, typical of a Scandinavian rural church used only for services. The second is that of a completely unheated building with an indoor climate closely following the fluctuations of the outdoor climate, including sub-zero temperatures in winter. The current state of knowledge on the subject of mechanical damage, and gaps in the knowledge, are discussed in connection with the two case studies. The case studies were chosen because they are interesting from an energy-saving perspective.

Two areas of research in particular where there is an evident lack of knowledge are identified. First, there is insufficient knowledge about the correlation between a fluctuating indoor climate and the risk of mechanical damage, i.e. the time-dependence of temperature and relative humidity fluctuations. Second, there is insufficient knowledge of how low temperatures affect the risk of mechanical damage.

Keywords

Historic buildings, mechanical damage, intermittent heating, low temperature

1. Introduction

The indoor climate in many Scandinavian historic buildings such as churches, palaces and manor houses often differs markedly from the indoor climate recommendations given for museums. Nonetheless, many of these buildings accommodate vulnerable and valuable objects and interiors. It is important to be able to assess the risks involved for these objects and to be able to predict the consequences that a change in the indoor climate may have, irrespective of whether that change has been made to improve the preventive conservation climate or for other reasons, for example to save energy. A sound scientific basis for understanding how the indoor climate affects the way materials degrade is required in order to take the right preventive measures. In an effort to illuminate some gaps in the knowledge within this area, we have conducted a review of the literature on research into the risks of mechanical damage to cultural objects caused by fluctuations in temperature (T) and relative humidity (RH). On the basis of this review, we have selected some specific areas where knowledge is limited, and we discuss these areas in greater depth in relation to two typical case studies. Finally, we offer some suggestions for continued research.

2. Background

Dimensional changes because of fluctuations in indoor climate can give rise to different types of mechanical damage to objects. Figure 1 shows schematically how the stress in a material is affected by the dimensional change (strain). Flaking or peeling paint and cracks in wood are examples of what in solid mechanics is referred to as fracture, while a permanent change in shape that does not result in fracture is termed plastic deformation. Plastic deformation starts when the stress exceeds the yield point (elastic limit), which defines the dividing line between the elastic area and the plastic area. Repeated or frequent stress in the elastic area can, however, in some cases give rise to deformation and fracture as a result of fatigue.

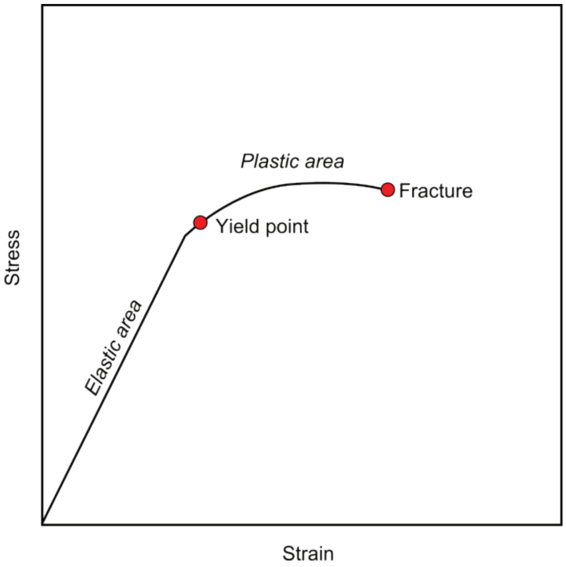

Figure 1. A typical stress-strain curve.

Hygroscopic materials absorb and emit moisture with changes in RH and T, which in turn gives rise to moisture movements in the form of swelling and shrinking respectively. Fluctuations in temperature also result in movement because of thermal dimensional change, which in most cases is negligible, however. If the movements are sufficiently great, stress can arise in the material, which can in turn result in fracture or plastic deformation. This applies to a material that cannot freely swell and shrink because it is restricted in its movement by another material that does not move in the same way, for example a coat of paint on a wooden surface. In reality there are no “free” movements, since certain parts of a material experience dimensional change quicker than others, which results in stress gradients in the material.

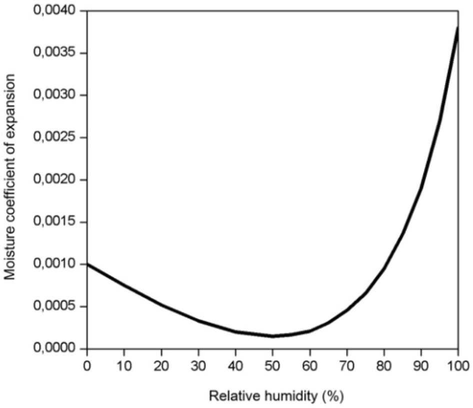

Figure 2. Moisture coefficients of expansion for cottonwood. The Y axis shows the relative dimensional change at a certain equilibrium moisture content. After Mecklenburg et al. (1998).

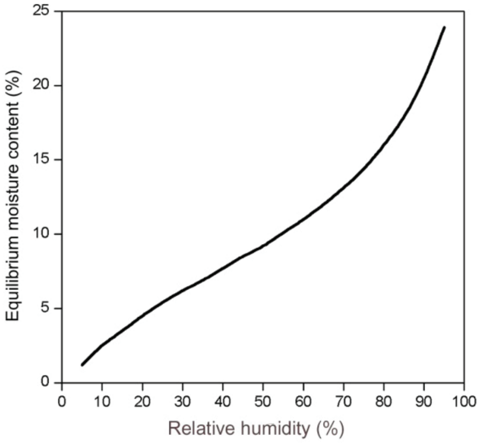

Figure 3. Sorption isotherm for wood at 21°C. From the Wood Handbook (1999).

The degree of the moisture movement in a hygroscopic material for a certain change in RH or T depends on what initial moisture content the material has. In general, the moisture movement is lowest for an equilibrium moisture content of about 50% RH, which is illustrated for wood in Figure 2. This phenomenon occurs because most materials emit and absorb least moisture when there is a change in RH in this area, which is illustrated by the somewhat lower inclination of the sorption isotherm; see Figure 3. The moisture content in a hygroscopic material is above all dependent on RH. The direct effect of the temperature has marginal significance, namely that the equilibrium moisture content is only slightly higher in the case of lower temperatures.

3. Overview of the knowledge

We have undertaken a review of the literature on research into mechanical damage caused by fluctuations in T and RH. In this section we present an overview of some of the research conducted in this area. In conclusion, we point to some less well researched areas where there is insufficient knowledge.

The way in which indoor climate recommendations have been developed for museums and storage facilities has been described elsewhere by, inter alia, Michalski (1993), Brown & Rose (1997) and Erhardt *et al.* (2007). Holmberg (2001) has described indoor climate recommendations in different countries and tried to trace their background. A shared conclusion is that there is no scientific basis for the recommendations for T and RH that have hitherto prevailed. The levels and allowable fluctuations that should be used for indoor climate control in individual cases is the result of a compromise, where the risk of mechanical damage is one of many factors.

The ways in which paintings on canvas and on wooden panels are affected by the indoor climate has interested many researchers. Berger & Russell (2000) have been carrying out tests since the 1980s on canvas paintings by measuring the forces that arise at the edges of the paintings. By removing the layer of paint from the canvas, they have been able to measure the forces that arise also in the composite structure. Similar methods have also been used by, for example, Hedley (1988) and Young & Ackroyd (2001). These studies have resulted in a significant increase in our understanding of the forces that arise in canvas paintings, and this knowledge can be used to understand the effects of different conservation measures. Where the effects of indoor climate are concerned, these studies have the character of basic research into materials science and methodological development, and it is difficult to draw any conclusions that could be applied in practice to the limit values for fluctuations in indoor climate.

The most influential research group in terms of studying mechanical damage to museum objects is represented by Marion Mecklenburg and David Erhardt at the Smithsonian Institute. For almost 30 years they have studied how moisture and temperature affect museum objects, and they have produced their own basic data from laboratory experiments. A general point of departure for their work has been that fluctuations that give rise to stress in the material's elastic area, that is to say that do not exceed the yield strength, can be considered non-harmful. They have demonstrated that stress that arises in hygroscopic materials because of changes in the moisture content corresponds to the stress that arises when an external force exerts stress on the material. Thus, they have been able to simulate the forces that arise because of fluctuations in T and RH by applying reliable mechanics-based testing methods (Erhardt *et al.* 1995; Mecklenburg *et al.* 1994). By experimentally determining the mechanical properties of the input material and then using numerical methods and computer simulations (the finite element method), they have established climate limits for some of the most sensitive objects in museum collections, above all canvas paintings and painted wooden objects. Their results show that there is no reason for the requirement for the very narrow climate limits that have prevailed. At the same time, they believe that some extremely sensitive objects should always be kept in humidity controlled display cases, where the climate can be kept as stable as possible (Erhardt & Mecklenburg 1994). Since the mid-1990s, they have worked to develop their own methods and to verify their studies. The climate limits and the method have been criticised but no-one has published any other alternatives (Erhardt *et al.* 2007). Their methods and their results have not, however, been extensively verified by other research groups.

The research into materials science has been a necessary, but thus far inadequate, basis for developing generally workable recommendations for a sound preventive conservation climate. Evaluations are required from qualified professionals, based on existing knowledge, experience and risk analysis. An important individual in this connection is Stefan Michalski at the Canadian Conservation Institute (CCI), who, while assuredly having done a large number of his own experimental studies of how objects are affected by indoor climate, has been primarily engaged in reviewing other people's results (Michalski 1991,1993). Amongst other things, his work has contributed greatly to the current ASHRAE Standards. Michalski advocates the concept of "proofed fluctuation", which can be used to determine limits for fluctuations in RH. The theory is based on the idea that the risk of new mechanical damage occurring is slight as long as an object is not exposed to greater fluctuations than those it has previously been exposed to (Michalski 1993, 2007). In order for this theory to apply, the climate history of the object must be known. Bratasz *et al.* (2007b) reason according to the same principle, although with different results, when they propose a method to determine allowable fluctuations based on the historic climate. Bratasz *et al.* emphasise the importance of limiting the short-term fluctuations, while Michalski views these as less important.

It is evident that the research done to date into mechanical damage is not particularly extensive and that what is lacking is a holistic approach that covers different categories of objects and indoor climate. Unfortunately, a characteristic feature of the research is often that of different groups of researchers pursuing their own theses and persisting in their own methods. Here, we will point to some aspects that have been inadequately studied.

Much of the research that has been done applies to a normal museum climate with a temperature of around 20°C and with a relatively stable RH. In many historic buildings the conditions vary very greatly, and the question is how this affects the allowable limits for T and RH.

Most researchers have not studied what effect a fluctuating indoor climate has on the incidence of mechanical damage, but experiments have been carried out with materials that have been allowed to approach equilibrium with ambient air. It is often pointed out that fluctuations over a long period can be great without the risk of damage occurring since the input materials have time to adapt. The speed at which a material is stressed can affect the degree of stress that occurs if the material is viscoelastic. There is little knowledge of how great this effect actually is for different historic objects. There is no common conceptual apparatus to describe the speed of fluctuations. Occasionally, they are divided into seasonal, 24-hour and short-term fluctuations, but how rapid a fluctuation is should in general be judged in relation to the reaction time of the affected object. It is not clear how this should be done in practice.

Much of the research done thus far has been based on laboratory experiments. There are no statistical studies examining the relationship between mechanical damage to objects in historic buildings and fluctuations in indoor climate.

There are no studies examining and quantifying the risk of deviating from currently recommended limits.

In the following section, we will discuss some of these aspects in greater detail. We have chosen to discuss the current state of knowledge on the basis of two typical cases: how painted wooden objects are affected in, on the one hand, an intermittently heated building, and, on the other, in an unheated building. These case studies have been chosen since they are of particular interest from an energy-saving perspective and because they also bring some of the problems mentioned above to a head.

4. Case studies

4.1. Intermittent heating

As early as the end of the 19th century, studies had been made of intermittent heating of churches (Fischer 1890), and in Scandinavia intermittent heating was for many years a commonly used heating strategy in many rural churches. The method involves rapidly heating the church so as to make it reasonably comfortable for congregations at church services and for visitors involved in other activities. Between these heating episodes the heating is turned off fully or partially. The advantages of this method compared with heating the church permanently are thought to be that it uses less energy and also that intermittent heating prevents the risk of excessively low RH in the winter. The rapid heating certainly gives rise to strong and short-term fluctuations in both T and RH, but several authors, for example Künzel & Holz (1991), take the view that sensitive objects are exposed to climate fluctuation for such a short period that they do not have time to react to the change. This view has been criticised by Camuffo (2006), amongst others, who believes that the repeated phases of heating can cause mechanical damage over time. Whether intermittent heating in general may cause damage has not, however, been proven in any scientific study.

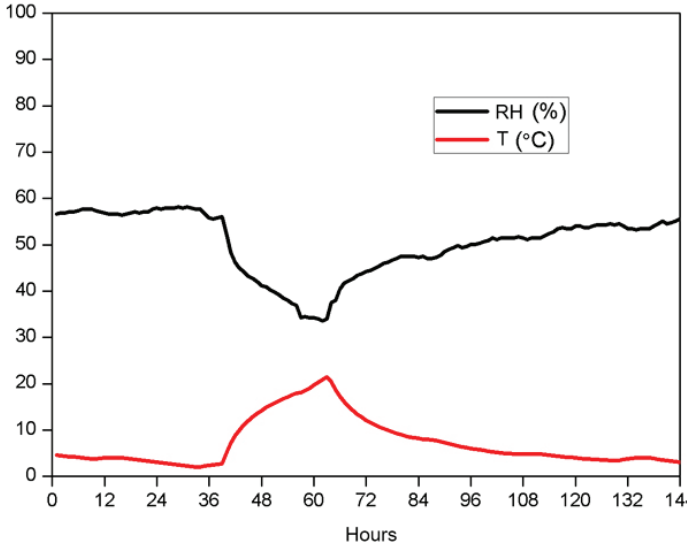

Figure 4. An intermittently heated church in northern Sweden. The curves show temperature and relative humidity in the central part of the church during one heating episode.

Figure 4 shows a typical variation in T and RH during intermittent heating. The air temperature increases rapidly when the heating is turned on. At the same time, RH decreases and the RH curve is almost a mirror-reflection of the temperature curve. The absolute air humidity is, however, affected depending on the humidity exchange, primarily at the external walls. In some cases even the moisture emitted by a visitor can significantly add to the humidity. Humidity exchange with walls has been studied by Padfield *et al.* (1994) and Broström (1996). How objects inside churches are affected has not been studied to the same extent.

When a hygroscopic material is exposed to fluctuations in T and RH, a moisture gradient develops in the material as well as a temperature gradient. As we have seen in the previous section above, this phenomenon has not been studied to any great degree, but the focus has been on the maximum forces that can arise between two equilibrium states. Moisture gradients are, however, highly relevant in connection with intermittent heating. In recent years, many researchers have become interested in studying the internal forces that can arise in wooden objects because of moisture gradients. The problem is highly complex and some factors that must be taken into account in analysing these forces are the moisture transport inside the material, the rate of diffusion in the surface layer, and the mechanical properties of the material. All these properties are dependent on both T and RH. The moisture transport at the surface is also affected by air movements. Wood is furthermore anisotropic, which means that it moves in different directions to different degrees. A further complication is the difficulty of measuring the moisture content at different depths in a material.

Olstad & Haugen (2007) have studied whether small movements in the surface of the wood, caused by intermittent heating, can cause damage to the paint layer. Their review of the research on the response time of different materials, that is to say how quickly the materials react to changes in T and RH, shows that the subject has been poorly investigated. Dionisi Vici *et al.* (2006) studied how 4cm thick boards of Poplar (*Populus alba*) wood reacted to step variations in RH, in order to understand how panel paintings react to fluctuations in indoor climate. The results of the study showed that the boards that were given a waterproof layer on one face reacted within minutes to climate fluctuations by changing shape because of internal differences in moisture ratio, while at the same time the adaptation to the equilibrium moisture content took several weeks.

Jakiela *et al.* (2008a) have shown, with the aid of numerical modelling, the distribution of the moisture ratio in wood for the duration of dynamic moisture sorption and desorption, and the intensity of the forces that arise, precisely in order to investigate the risk of damage because of intermittent heating. The numerical modelling was done for a solid wood cylinder, imitating the symmetry in a sculpture carved from a tree-trunk. This geometric shape was chosen to simulate the instances that give rise to the greatest internal stresses. The modelling results were used to determine which fluctuations in RH give rise to reversible and irreversible shape changes respectively. The results were compared with measurements taken both of wood samples in the laboratory and *in situ* in a church in Rocca Pietore, in northern Italy. Two painted wooden objects from the church's altarpiece were examined, one a head with a diameter of 15.5 cm, and the other a finger with a diameter of 0.5 cm. Acoustic emission was used to measure stress levels in the objects, and dimensional changes were measured with laser instruments (Jakiela *et al.* 2008b; Bratasz *et al.* 2007a). The results of these studies point to the possibility of using numerical modelling as a method for determining safe limits for fluctuations in RH and T. This does, however, require the model to be developed and validated by means of more experiments.

An important precondition for simulation modelling of objects is that one has the correct input data. These data can be difficult to obtain using non-destructive methods, but one practicable approach is to carry out tests on replicas of historic objects. Allegretti & Raffaelli (2008) examined the moisture-transporting properties for different historic paint treatments on wood using this procedure. The results of their investigations could be used to, inter alia, simulate the effect of a fluctuating indoor climate. One circumstance that complicates the simulation of deformation and damage in old, painted wooden objects is that, unlike newly made objects, old objects have often developed cracks which greatly affect the moisture and heat transport as well as the intensity of the stresses that occur.

In view of the fact that intermittent heating is a much-used heating strategy, which also brings with it significant energy savings, there is a need to be able to establish safe limits for the fluctuations in T and RH. Some key questions in this respect are:

- What heating rate is just right? How long can heating continue after the desired temperature has been reached? This has an impact on both the amount of energy consumed and the dimensioning of the heating system. Rapid heating increases the risk of damage because of moisture gradients, while slow heating increases the risk of damage because thin objects will approach equilibrium.

- Given the complexity of the problem, is it possible to arrive at a set of criteria that are generally applicable?

- How will the initial RH level affect the allowable fluctuations? The dimensional change coefficient is lowest at a moisture ratio of around 50 % RH, so the initial moisture ratio in the material should be of decisive importance.

- Is there cumulative material degradation because of repeated heating cycles and to what degree has the object adapted through deformation? Is there a risk of material fatigue?

The knowledge we have today is not sufficient to enable us to answer these questions. In order to find an optimal

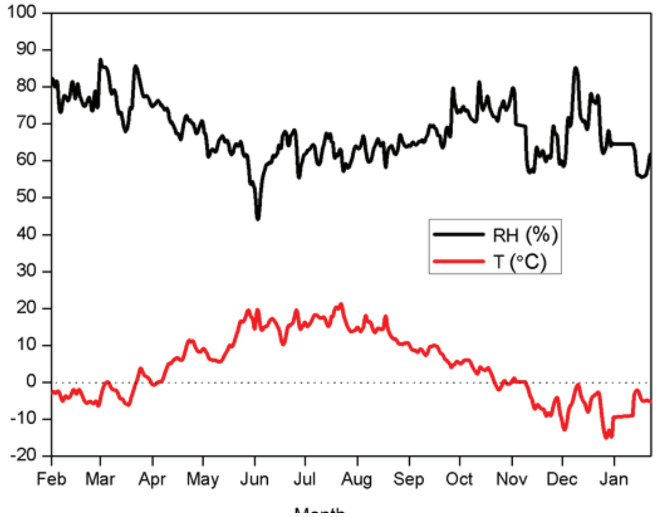

Figure 5. An unheated church in northern Sweden. The curves show temperature and relative humidity in the central part of the church for a period of one year.

compromise between comfort, preservation and energy-saving, more research is required on the effect of intermittent heating on objects and buildings.

4.2. Low temperatures

Many historic buildings in Scandinavia are not used in the winter. Consequently, climate management during the cold period can only be done based on the needs of the objects and the building. Figure 5 shows the climate over the course of a year for an unheated wooden church in the far north of Sweden. The indoor climate in winter is typical of an unheated building, cold and damp. For a large part of the winter, there are below-zero temperatures inside the building. The question is to what extent this climate gives rise to mechanical damage, and how the risk of damage can be reduced through climate control? The current recommendations are frequently for a lower temperature limit, aimed at improving the preventive conservation climate, which makes the question interesting from an energy-saving point of view, since energy consumption is proportionate to the temperature difference between outside and inside. Low temperatures also reduce the rate of chemical degradation, which for some materials can be extremely important.

The effect of low temperatures on museum objects has primarily been studied in connection with fighting insect infestations, when objects have been subjected to very low temperatures for short periods in order to kill pests. A review of the literature on how this affects objects has been undertaken by Carrlee (2003). One important detail in this connection is that the wooden objects that undergo low-temperature treatment are wrapped in close-fitting polythene bags, which reduces the amount of available moisture that can condense in the material. This is a decisive difference compared with the objects in a cooled building. Composite objects made of different materials with different thermal expansion coefficients run the risk of damage in the event of temperature fluctuations. This effect should be negligible compared with the moisture-related dimensional changes in the case of objects that have contact with ambient air (Mecklenburg & Tumosa 1991).

One of the factors that influence the effect of temperature on different materials is glass transition temperature (T_g). This is the temperature at which polymers and organic materials transition from a less hard state at higher temperatures to a harder and more brittle state at lower temperatures. This happens at the same time as the material shrinks.

T_g is affected by different factors; for example, age can increase T_g, while slow cooling can lower T_g. Elastic deformation normally occurs only when the temperature exceeds T_g (Carrlee 2003). Mecklenburg & Tumosa (1999) take the view that damage that occurs in painted objects may well be attributable to low temperatures because paint materials often have a relatively high T_g. Where temperatures are lower than T_g, objects are particularly sensitive to mechanical forces that arise from handling. One factor that should be able to balance this out is that low temperature often coincides with high RF and thus a high moisture ratio in the material. Since most materials become more flexible at a higher moisture ratio, this reduces the risk of mechanical damage somewhat.

The risk that objects will suffer frost damage as a result of low temperatures is often mentioned as an argument in support of maintaining an above-zero indoor temperature in winter. The amount of water absorbed by the material, the physical phase it is in, and how the water is bound to the pore walls of the material determines whether it will freeze, expand and thus damage the object. The risk that objects will be damaged because of frost damage in unheated historic buildings is probably very small, however, because even at very high RH the pores do not contain sufficient moisture (Carrlee 2003).

The rate of diffusion of water vapour between the object and the air, like the rate of diffusion in the material itself, is highly dependent on temperature. Thus, it takes longer for an object to absorb and emit moisture at low temperatures, which means that dimensional changes caused by fluctuations in RH are not as strong and rapid, as it takes much longer for the moisture ratio in the material to adapt to the surroundings and achieve equilibrium moisture content. The way in which the internal moisture buffering of the surface is affected by low temperatures, that is to say what temperature and moisture gradients will arise, appears largely to be un-researched. Carrlee (2003) claims that most of the existing information on the risk of moisture-related damage occurring at very low temperatures is theoretical and extrapolated from research done at higher temperatures.

5. Discussion

While the amount of research done on the risk of mechanical damage to cultural objects caused by fluctuations in temperature (T) and relative humidity (RH) is extensive, the area of research itself is still emerging. For certain practical applications, there is no critical mass of research on which rational decision-making ought to be based. Uncovering the connection between indoor climate and damage to objects is no simple task. Every object is unique and has its own history and origin and its own climate history. Laboratory tests on individual materials cannot simply be transferred directly to complex and aged artefacts. On the other hand, it can be extremely difficult to carry out non-destructive measurements in the field, especially of the stresses that arise in objects because of a fluctuating indoor climate. Statistical studies comparing damage to objects and different indoor climates is one alternative that has not been tried to any greater extent.

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Paper II.

Uncertainties in damage assessments of future indoor climates

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Abstract

A significant amount of uncertainty is generated in the process of combining projections of future climate, building simulations and damage functions to produce risk maps for historic buildings. The objective of this paper is to identify and qualitatively describe the main uncertainties in the production of such maps. The main sources of uncertainty for each modeling step are identified. It is concluded that the level of uncertainty in risk maps is so high that deterministic approaches have severe limitations, and that further research is needed to assess the levels of uncertainty introduced by each modelling step.

1. Introduction

Climate change projections and building simulations can be combined to produce scenarios of future indoor climates in historic buildings. Risks to the building or the interiors related to the indoor environment can be assessed with damage functions. The European Climate for Culture project (www.climateforculture.eu) uses this approach and applies it across all of Europe. Instead of using specific, actual buildings, a set of generic buildings are used to transfer outdoor conditions to indoor conditions. In this way it is possible to produce maps of future climate-induced risks to historic buildings and their interiors. The information can be used for climate change impact assessment and for adaption planning of the built cultural heritage. A significant amount of uncertainty is generated in the process of combining projections of future climate, building simulations and damage functions. In this paper we attempt to disaggregate the sources of uncertainty involved in this process.

Climate scenarios describing the future climate are associated with uncertainty, rising from inadequate knowledge of the climate system, imperfections in the numerical climate models and inherent variability in the climate system e.g., [1]. Building simulations and damage functions do not only propagate uncertainties in the climate scenarios but also add new elements of uncertainty.

In a review of probabilistic approaches for climate change impact studies on buildings, Wilde and Tian [2] conclude that although there are strong reasons for such studies to be of probabilistic nature, only a few studies consider uncertainty explicitly. With an unknown, but presumably high level of uncertainty, the results might be practically useless.

The lifespan of building services, changes in use, interventions to the building envelope and other changes in the building and its context play a significant role in long-term prediction of building performance. These changes may overshadow the impact of climate change and therefore limit the applicability of climate change impact and adaption studies to buildings [2]. Historic buildings, particularly if they are unheated, change less in these respects than standard commercial or residential buildings. Climate change impact and adaption studies therefore seem especially useful for historic buildings. Generally, cultural heritage management aims at preserving for the far future, which further motivates the study of the impact of climate change.

The approach of simulating the future indoor climate of historic buildings based on regional climate projections has been used in a number of recent studies [3–7]. Essentially these studies present a method. The uncertainty in the results is not dealt with, with the exception of Lankester and Brimblecombe [5], who compare three different emission scenarios.

If the propagation of uncertainties is not dealt with there is a risk that data will be used in ways that cannot be supported. If uncertainties are obscured in the final output and described in a deterministic way, decision-makers might come up with adaption strategies that are worse than if no information had existed [8]. The way forward is to address the uncertainties in every step by means of reduction, quantification and communication. A natural starting point for this is to analyze the sources of uncertainty throughout the process.

The objective of this paper is to identify and qualitatively describe the main uncertainties in the production of risk maps based on predicted indoor climates and damage functions.

2. Uncertainty in Risk Maps

Much effort has been made to describe and categorize uncertainty in climate change impact and adaption studies e.g., [9,10], and a consistent and transparent treatment of uncertainty is a prioritized task for the climate change research community e.g., [11]. A common division of the nature of uncertainty is between epistemic and aleatory uncertainty. Epistemic uncertainty comes from a lack of knowledge about a process.

It could therefore, in theory, be reduced with a more complete understanding. In practice, it is not always possible to reduce the uncertainty of complex systems, such as the global climate. Aleatory uncertainty, also known as stochastic uncertainty, originates from randomness in nature and the inherent variability in systems. The word aleatory is derived from the Latin word for die, ālea, and the randomness in a closed system such as a pair of dice illustrates this kind of uncertainty. Aleatory uncertainty cannot be reduced; it is a property of the phenomenon being studied. Refsgaard et al. [9] suggest a third kind of uncertainty, ambiguity, which 'results from the presence of multiple ways of understanding or interpreting a system'. To some extent, it is possible to represent both epistemic and aleatory uncertainties with probabilities; this is not the case with ambiguity. Ultimately all kinds of uncertainty stem from a lack of knowledge, and in practice there is no clear division between the different natures of uncertainty discussed here.

The uncertainty cascade of producing risk maps is shown step-by-step in figure 1. The sources of uncertainty in each step will be discussed in the following sections.

2.1. *Uncertainty in forcing conditions*

Changing concentrations of greenhouse gases and aerosols in the atmosphere lead to changing radiative properties of the atmosphere. Changing land use has an impact on surface albedo and surface heat and water fluxes. Changes in the intensity of solar radiation and large volcanic eruptions also have an impact on the climate. Historically, it is clear that anthropogenic forcing agents have dominated over the last centuries and that the result is global warming [12]. The uncertainties are comparatively small concerning the influence of greenhouse gases while they are much larger for the aerosol forcing and also, relatively, for changes in the solar insolation.

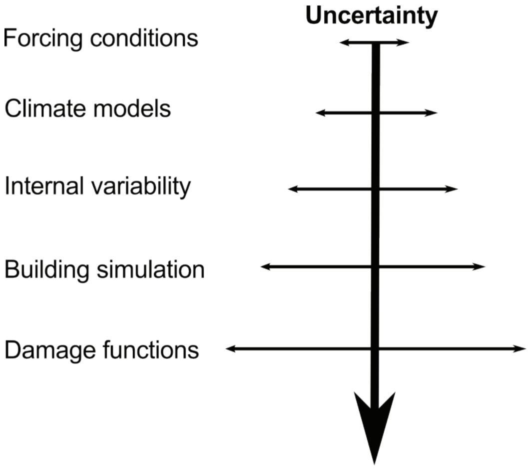

Figure 1. The uncertainty cascade in risk maps.

For the future, uncertainties in the forcing conditions are related to all of the forcing agents mentioned above. Emission scenarios like the ones suggested in the Special Report on Emissions Scenarios (SRES) [13] from the Intergovernmental Panel on Climate Change, or the more recent Representative Concentration Pathway (RCP) scenarios [14] all include a large number of different possible pathways into the future and there is no judgement about their likelihood. The SRES scenarios do not include mitigation scenarios, while the RCP scenarios do. Hence, the total uncertainty range is in fact somewhat larger in the newer RCP scenarios. These scenarios pertain only to the anthropogenic forcing agents; changes in solar forcing and volcanic activity are not included.

2.2. Uncertainty in climate models

Climate models are highly complex numerical models of the climate system. Due to limitations in computer power, the models cannot resolve all relevant processes and those that are included are often described in a simplified way. Horizontal grid spacing of typically 100-300 km in global models and 10-50 km in regional models implies that phenomena at smaller scales, including for instance clouds and turbulence, cannot be treated explicitly in the models. Instead, they need to be described by large-scale parameters that are available in the models. This is referred to as parameterization and is one of the main sources of errors in the climate models. Other uncertainties are related to the fact that we do not know how the climate system works in all its details. Also, all relevant processes may not be included due to computational limitations. For instance, it is only recently that carbon-cycle models have been coupled to climate models with a potentially strong impact on the results [15].

As a result of differences in their formulation, different climate models will project slightly different climates. This is true both in today's climate but also in future and past climates. Differences between models result in both different long-term global average conditions and different regional details in the climate, including extreme conditions. Furthermore, different climate models respond differently to changing forcing conditions.

2.3. Uncertainty related to internal variability

The climate is highly variable with variations at many different time scales. Part of the variability is driven by changes in external forcing as described above (e.g., volcanoes, solar irradiation, etc.). But, even if there is no external forcing, the climate will undergo changes. Such variability is referred to as internal variability and it can be associated with different phenomena such as the El-Nino affecting a large part of the Pacific Ocean and surrounding continents e.g.,[16]; or the North-Atlantic Oscillation that has a profound impact on weather and climate in much of Europe [17].

As climate models are designed to simulate the climate system they also include internal climate variability e.g.,[18]. An implication of this is that in simulations when external forcing is changing over time, as in the twentieth and twenty-first centuries, there is a component of internal variability that is part of the overall climate change signal. In some cases such internal variability can amplify the externally driven climate change signal and in some cases it can reduce it.

Climate model integrations often span the time range from c. 1850 to 2100, thus including both historical changes and a future scenario. Starting conditions in 1850 are taken from a control integration with the same model run for several hundred years with constant pre-industrial forcing. These starting conditions will differ from the state of the real climate system at that time. This, in turn, means that the internal variability in the model integration will not be in phase with that of the real climate system. Another experiment with different starting conditions will not be in phase with the first one and the differences between these simulations can be taken as a measure of the uncertainty related to internal variability. Recent findings indicate that the contribution of internal variability may account for at least half of the inter-model spread in projected climate trends during 2005-2060 in the multi-model ensemble used in the fourth assessment report by the Intergovernmental Panel on Climate Change [19]

2.4. *Uncertainty in building simulations*

Based on projected future outdoor climate and building properties, the future indoor climate is predicted through building simulation. The simulation model can be more or less complex, ranging from whole building simulations to linear functions based on a statistical analysis of measurements.

Whole hygrothermal building simulations with large datasets are time-consuming and it is unrealistic to perform them for all locations that can be handled by regional climate models. A shortcut is to use rather simple transfer functions, which give the indoor climate as a function of the outdoor climate. Lankester and Brimblecombe use a linear function [3,5]

$y=a+bx$ where

y = indoor temperature or mixing ratio
x = outdoor temperature or mixing ratio
a, b = regression coefficients determined for each month

This transfer function gave a reliable estimate for temperatures but for relative humidity the estimate was less reliable. Bratasz et al. [4] also use the same kind of transfer function but they introduce a time delay for temperature. Nik et al. [20] show that the hygrothermal conditions inside four attics in Sweden are complex non-linear functions of the outdoor conditions, i.e., the variability inside does not follow the outside variability. A linear transfer function would consequently not be able to model this behavior.

The linear fit methodology provides a first-level approximation but there are other methods that better reproduce hysteresis cycles, especially the daily one. In an approach used by Camuffo et al. [21] the forcing factor is an external (daily or seasonal) temperature cycle, and the indoor temperature is obtained by means of a conduction heat transfer based on the heat diffusion equation in Cartesian coordinates. The method results in a time-dependent equation that expresses the heat flux in terms of the current temperature and the past histories of both temperature and heat flux.

Huijbregts et al. [6] use the building simulation model HAMBase to calculate the indoor climate from the predicted outdoor climate. The model gives a good agreement with measured values for temperature. For relative humidity the agreement is better than for the simple transfer functions, but there is still a significant error.

To produce risk maps it is advantageous to use generic building types for the simulation of indoor climates. One generic building type is supposed to represent a category of actual buildings, an approach previously used by Crawley [22]. Although this methodology seems to have potential, it has not been widely used and the common approach is to use selected case study buildings [2].

Essentially, there are three sources of uncertainty in building simulation, irrespective of the complexity of the used model [23]:

1) *Specification uncertainty* due to discrepancies between the building and the model. In general, this uncertainty is higher for historic buildings as the composition of the building envelope might not be known and the physical properties of old building materials vary more within and between buildings. The use of generic building types for simulation introduces a high level of specification uncertainty. The level of this uncertainty is a matter of how well the types represent actual buildings. It can be reduced with the use of a larger set of generic buildings, thereby better representing groups of actual buildings.

2*) Modeling uncertainty* due to deficiencies in the model itself. This includes uncertainty of microclimates in the building. The level of modeling uncertainty with transfer functions is higher than for whole building simulations. Nik et al. [20] studied the effect of climate change on typical Swedish attics. They showed that the difference between three different emission scenarios was insignificant for the risk of mould growth. Interestingly, this could be explained with the higher shortwave radiation intensity of the low emission scenario that showed less cloud than the other scenarios. With the use of a simpler model, omitting solar radiation, this effect would have been obscured.

3) S*cenario uncertainty* due to uncertainties about external conditions, such as climate conditions and changes to the building or the use of the building. Included in this category is the conversion of data from climate projections to the temporal and spatial resolution needed for building simulation, usually hourly values for a given location. Climate model projections deliver values representative of an area, which have to be downscaled to a specific location. This additional downscaling adds further uncertainty, which can be high, particularly for locations with complex topography. In a long-term perspective, changes can be expected in the use of a building, in climate-control systems and in the building envelope. Any model validated for the present conditions will thus be more or less valid for the future.

In summary, it is clear that the use of generic buildings and transfer functions, as opposed to real buildings and whole building simulations, introduces more uncertainty. Despite the added uncertainty it seems as if this approach is the most viable option for the production of risk maps. By comparing case-study buildings with generic buildings, as well as transfer functions with whole building simulations, it would be possible to assess the difference.

2.5. Uncertainty in damage functions

In this paper we use the term damage function to describe a quantitative expression of cause and effect relationships between environmental factors and material change. We suggest that uncertainties in damage functions originate from three fundamental sources:

1) *Input uncertainty*. This is uncertainty of the properties of objects as well as uncertainty of input data. Many damage functions are based on the behavior of one single material and are not representative of the wide variety of forms in which different materials are found in heritage objects. For example, the material 'paper' could be old, new, acid, alkaline, have high or low lignin content and be in the form of a single sheet or a book. All these factors would affect the response, but they may not be included in the damage function.

The uncertainty of input data arises from uncertainties in measured or predicted data. One problem is the formation of microclimates, i.e., the climate might differ significantly within a room and therefore not be representative for the deterioration mechanism of concern. Another problem is that in hygroscopic materials several deterioration mechanisms e.g., swelling-shrinking, hydrolysis, corrosion, mould growth, hydration and mineral transformation, depend on moisture content. However, as moisture content is difficult to measure, relative humidity is often used as a proxy in damage functions. In reality the relationship between moisture content and relative humidity is dynamic, characterized by cycles and fluctuations and the temperature of an object is not the same as the air temperature. In addition, heat diffuses faster than moisture in hygroscopic materials, causing internal unbalances under dynamic conditions.

2) *Deficiencies of the function itself and the natural variability of the deterioration process*. There might be synergistic effects that are not included in the function. This uncertainty is rarely quantified but it should be possible to produce probabilistic damage functions in many cases.

3) *The interpretation of the output, i.e., the predicted material change*. This is a significant source of uncertainty due to ambiguity. Most damage functions will only predict a relative change. If generic buildings are used this is not necessarily problematic, as there are no actual objects for which absolute damage could be predicted. Furthermore, it is uncertain to what extent a material change will be interpreted as damage; it is by nature subjective.

The significance of uncertainties in the predicted indoor climate resulting from climate projections and building simulation will vary for different types of cause-effect relationships, as these are not equally sensitive to variability or extreme climatic events.

The type of relationship that is most straightforward to model with a damage function is one where the effect can be expressed as the product of the intensity of a physical variable and its duration, which is known as a dose-response relationship. One example is colour fading which depends on the product of light intensity and time. Most deterioration mechanisms are not strict dose-response relationships although there may be cumulative effects over time. Some of these can be described with relatively simple functions depending on one or more variables. One example is the chemical deterioration of paper due to cellulose hydrolysis, which can be approximately predicted by combinations of relative humidity levels and temperature resulting in the same relative rate of deterioration.

When the cause-effect relationship is neither a dose-response, nor a simple function of one or more physical variables, the problem is more complex. Furthermore, the functional variables might be mixed and involve synergisms. In these cases it becomes more difficult to mathematically describe the relationship with a damage function.

An example of one such complex cause-effect relationship is mould germination and growth. Most models use a combination of relative humidity, temperature and time for prediction e.g., [24]. The germination of mould is a threshold phenomenon and therefore sensitive to extreme conditions for a limited period of time. Mould growth, on the other hand, is cumulative. Although it is not well established how variability in temperature and relative humidity affect mould, it has been shown that fluctuating relative humidity decreases growth of mould also in relation to cumulative time at relative humidity levels that permit growth at constant moisture conditions[25].

Given the fundamental differences in time-dependency and cumulative effects between different damage functions it seems plausible that uncertainties in predicted indoor climates will play different roles for different types of functions. For example, uncertainty about variability and extreme events will be of less concern for cellulose hydrolysis than mould germination and growth.

Further research is needed to establish the sensitivity of damage functions in relation to upstream uncertainties. With the current state of knowledge this is more or less guesswork.

This overview has pointed at possible sources of uncertainty in damage functions but not discussed their magnitude. Although the sources are many, it is not the case that most damage functions are saturated with uncertainty. Many damage functions which are derived from laboratory work perform well when tested on heritage objects in a museum environment.

3. Discussion

As shown in the previous section, there are significant uncertainties introduced at each modeling step in the production of risk maps. The sources of uncertainty and their dominating nature are summarized in table 1. The relative levels of these uncertainties and how they propagate through the process to produce risk maps are to a large extent unknown. Furthermore, little is known about how important this gap in knowledge is for the final assessment of risk maps, both in the case of estimated impact and for adaption planning. A common definition of risk is probability times consequence. Actually the term risk map is misleading for the type of map discussed in this paper, if the aspect of probability or likelihood is excluded. An intuitive direction of research to bridge this gap would be to quantify uncertainties for the whole chain. In this vein, Tian and Wilde [26] outline the methodological steps needed for a probabilistic treatment of building performance in relation to climate projections, based on global sensitivity analysis. This methodology could be extended to include damage functions. As mentioned above, there is a need for sensitivity analysis to analyze how damage functions are affected by upstream uncertainties from climate projections and building simulation.

The use of building simulation and damage functions as an extension to climate projections is a top-down approach where the output is a predicted value (with the possibility to add a probability range). There

Modelling step	**Major source of uncertainty**	**Dominating nature of uncertainty**
Forcing conditions	Socio-economic pathways	Ambiguity, epistemic
Climate models	Model deficiencies	Epistemic
Internal variability	Randomness in nature	Aleatory, epistemic
Building simulations	Specification	Epistemic
	Model	Epistemic
	Scenario	Ambiguity, epistemic
Damage functions	Input	Epistemic
	Deficiencies of the function	Epistemic, aleatory
	Interpretation	Ambiguity

Table 1. The major sources of uncertainty for each modeling step in the production of risk maps and the dominating nature of uncertainty for each source. Adapted from [9].

is a possibility to use a bottom-up process instead, where intolerable risk is expressed as a combination of thresholds for different climatic parameters. The likelihood of exceeding these thresholds would then be analyzed and used for risk assessment [27].

However, it is only possible to quantify a limited part of the whole uncertainty range, as shown in figure 2. In effect, there will always be a large amount of residual uncertainty left, despite the best efforts of research. Whereas aleatory and epistemic uncertainty can be quantified to some extent, ambiguity is not amenable to quantification at all. From the summary in table 1 it is evident that there are important sources of uncertainty in risk maps, which are by nature ambiguous. As pointed out by Dessai and Hulme [28], uncertainties about future climate change will always be subjective and conditional, and further research might actually increase uncertainty as new unknown uncertainties are discovered. This is a strong argument that adaption planning should not rely on increasingly precise predictions, i.e., reduced uncertainty. Instead, adaption measures could be implemented that are robust for a range of possible future climates and states of the world [29, 30].

All risk management decisions, and consequently all adaption planning decisions, do not require the same level of treatment of uncertainty; sometimes best-estimates or worst cases are sufficient for decision-making [31]. The use of worst cases is widely used for decision-making in preventive conservation, and many damage functions are based on this concept. Even though worst cases are appealing because of the intuitive ease with which they seem to inform decision-making, they are most useful in the case of a negative result, i.e., that climate change will not matter for the object under consideration. However, this result will be obvious if a wider range of probability distributions are considered. Furthermore, it is not an easy task to define the worst case given the many modeling steps needed to produce risk maps. For each modeling step some moderation of the worst case is needed in order to ignore extremely unlikely outcomes. This moderation results in a

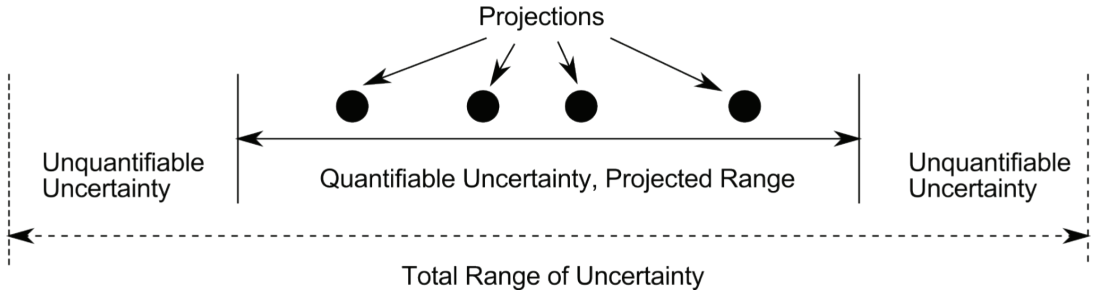

Figure 2. The relationship between damage projections, a projected range and a total range of uncertainty. Adapted from [10].

quasi-worst case that represents a truncation of the probability distribution. Both quasi-worst cases and best-estimates can be problematic when used for policy decisions [31, 32]. The limited resources available for cultural heritage make trade-offs between risks a necessity, and such trade-offs are best done in a risk management framework where the overall magnitudes of different risks are compared.

A final question is how risk maps should be designed and selected, given the high level of uncertainty involved. To answer this question, there is a need to define who the likely end-users are. If politicians are the intended audience it may be necessary to conceive a few generic risk combinations that summarize changes due to climate change. Conservation students would want as many maps devoted to hazard-material interaction as possible. The stakeholder with administrative responsibility for a given site or group of sites would probably not need the generalized output of a map but require specific data about that one location, as maps only can give generalized views over large geographic areas.

Despite the many challenges ahead, it should be the aim of research to assess the relative importance of different uncertainties and to communicate uncertainties effectively to decision-makers [33]. How uncertainties should be communicated in risk maps is a further topic of study. Effective communication of uncertainty is a challenging task, even when full probability distributions are known [34].

4. Conclusion

The objective of this paper was to identify and qualitatively describe the main uncertainties in the production of risk maps based on predicted indoor climates and damage functions. The main sources of uncertainty in each step of the modeling process were disaggregated and discussed. The key findings are that:

- the level of uncertainty in risk maps is so high that deterministic approaches have severe limitations. As an alternative, uncertainty could be addressed by the use of a probabilistic approach. However, there will always be a significant amount of residual uncertainty that cannot be quantified.

- each modeling step introduce significant uncertainty, and the relative levels of these uncertainties need to be further studied.

Although the final level of uncertainty in risk maps will be high regardless of whether a deterministic or a probabilistic approach is used, risk maps based on state-of-the-art scientific knowledge are valuable as indicators of future risks to cultural heritage and they will play an important role in informing mitigation and adaption planning at different levels.

5. Acknowledgements

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Paper III.

The indoor climate in Skokloster castle

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Abstract

Skokloster castle is a heavy stone and brick building without any active climatization. It houses a large collection of artefacts shown in their historic environment without any showcases. The objective of this study is to analyse the indoor climate, make a risk assessment and to propose interventions to improve the indoor climate with respect to the long term preservation of the collection. Relative humidity and temperature have been monitored within the castle for more than one year. Air exchange in selected rooms has been measured quarterly using diffusive sampling. The indoor climate is characterized by extremely low temperatures and high relative humidity in the winter. Even though the building does reduce the effect of outdoor variations, the variations in the indoor climate are larger than one would prefer in a museum. The primary risks associated with the indoor climate are mould growth, mechanical damages and chemical degradation. The variations in RH can be reduced by enhancing the effective hygrothermal inertia of the building through a reduction of the air exchange. In order to substantially reduce the mould risk, conservation heating and/or dehumidification would be needed.

Keywords

Indoor climate, risk assessment, historic buildings, museums

1. Introduction

Skokloster castle, located on a peninsula in Lake Mälaren north of Stockholm is a heavy stone and brick building, completed in 1767 see fig. 1. The impressive four-storey building forms a quadrangle around a central courtyard with octagonal towers in each corner. An inner corridor, which is in direct connection with outdoor air through the staircases, connects the rooms. The castle is built with brick walls on a granite foundation. The façade is rendered and has lead-glass windows with limited air tightness.

The castle is open for visitors mainly during the summer

The castle contains about 50000 objects, mainly from the 17th century. Of these are about 20000 in the library on the fourth floor. “Wrangel’s Armoury”, also on the fourth floor, contains about 2000 objects, mostly weapons, but also ethnographic and natural history artefacts. In addition to these collections, the castle is extravagantly furnished with stucco ceilings, woven tapestries, furniture and works of art. Since 1716 a detailed catalogue of the artefacts room by room has been kept, including comments on the condition of the artefacts. The artefacts are shown in their historic environment without any showcases.

The indoor climate and the collection at Skokloster castle have been under observation for centuries. It is widely known as a building with stable indoor climate and a relatively good indoor climate with respect to preservation.

In many rooms there are open fireplaces and ovens, but the upper floors have had practically no heating for 300 years. Nowadays, some rooms in the ground floor are heated all year round, but apart from this no active climatisation in the castle. An exception is a small electric heater that was put in the library after an outbreak of mould. On the upper floors, the doors are closed and opened to control air exchange and curtains are used to control solar radiation.

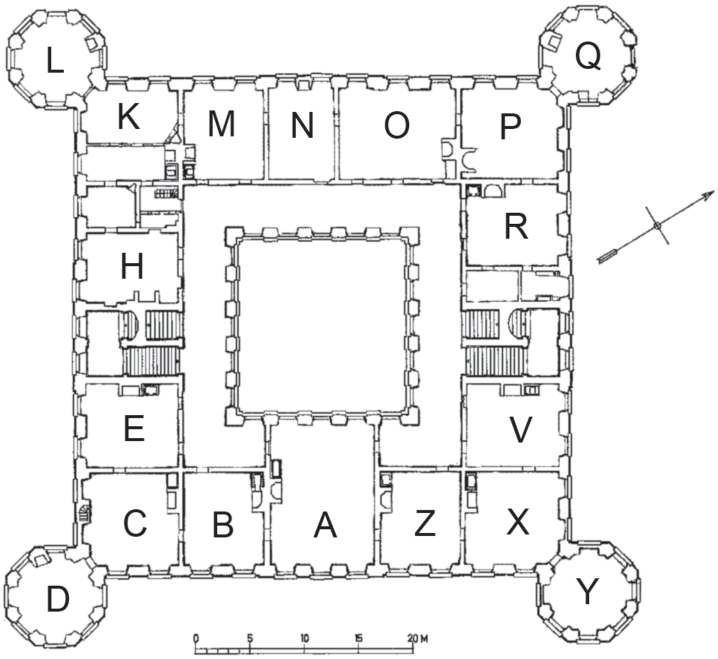

Fig. 1. Skokloster castle. The rooms are numbered in the same way on all floors, e.g. room 2A is situated under room 3A.

The objective of this study is to:

- Make a quantitative description and analysis of the indoor climate,
- Assess the indoor climate in relation to major risks to the collection,
- Understand how building properties and outdoor climate variations influence the indoor climate,
- Propose interventions to improve the indoor climate with respect to the long term preservation of the collection.

This is first step in a series of investigations aiming to facilitate a long term sustainable management of the castle and to generate more knowledge on low energy climate control strategies for this type of buildings.

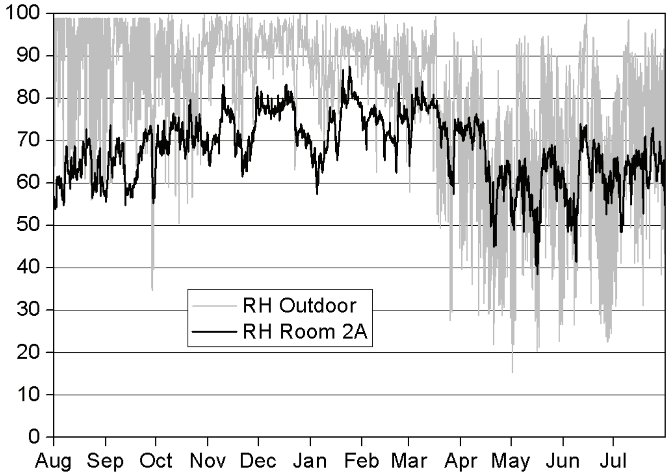

Fig. 2. RH in room 2A compared to outdoors.

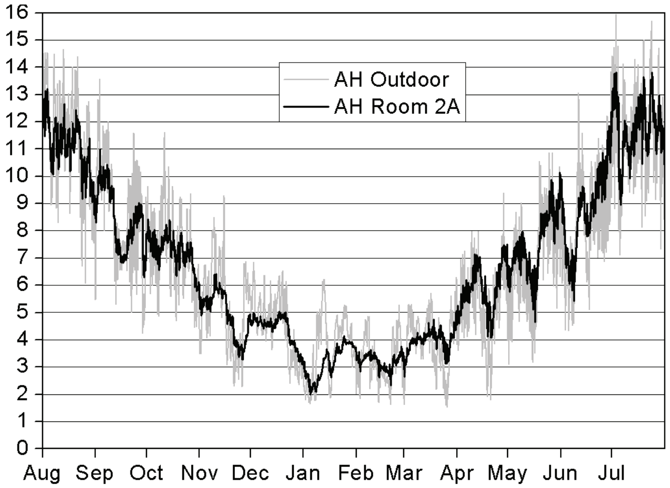

Fig. 3. AH in room 2A compared to outdoors.

2. Method

In order to describe the indoor climate with high resolution, relative humidity and temperature have been monitored within the castle for more than one year. Air exchange in selected rooms has been measured quarterly using diffusive sampling. All events in the castle that may influence the indoor climate, such as the use of curtains and the opening of doors to enhance air circulation, have been logged daily.

Measurements have been made in 44 locations covering 27 rooms. Most of the loggers were placed in the middle of the room at a height of 1,8m. In the present analysis, the heated rooms on the bottom floor were excluded. The following twelve rooms on floors 2 - 4 were selected, 2A, 2K, 2R, 3A, 3K, 3R, 4A, 4C, 4K,4R (Fig. 1).

Starting June 2008, temperature and relative humidity is logged every hour. The present investigation is focused on data for one year: August 2008 until July 2009.

Gemini data loggers of type Tinytag 2 Plus were used with a recording interval of one hour. The loggers were new and factory calibrated within the following specifications:

Resolution: 0,01 °C / RH <0,3 %,

Inaccuracy: 0,45 °C / RH 3 %.

For RH, the logger has an estimated time constant of 25 minutes.

The temperature sensors were not shielded, thus the recorded values will reflect the operative temperature including radiative effects of the walls.

For the outdoor measurements, a Testo 6681 transmitter with a Testo 6614 heated probe was used to eliminate condensation problems at low temperatures. At some times, RH outdoor values may have been influenced by indirect heating from the sun. The outdoor measurements have been compared to data from the weather station in Uppsala 20 km north of Skokloster, provided by the Swedish Meteorological and Hydrological Institute. No major differences were found. Measurements of wind speed are from the weather station in Uppsala Air exchange was measured using a tracer gas test according to NORDTEST Standard VVS118.

3. The present indoor climate in Skokloster castle

Fig. 2-4 shows time series of temperature (T), relative humidity (RH) and absolute humidity by volume (AH) in room 2A, selected to be representative for the whole building. It can be seen that all three parameters follow both the seasonal and short term variations of the outdoor climate but that the building does reduce the effect of short term outdoor variations significantly. It does appear as if T is more stable than RH and this is also verified by a statistical analysis. However T readings are influenced by the walls, as mentioned above, and therefore can be expected to be more stable.

Fig. 5 shows statistics for RH in 12 rooms from floors 2, 3 and 4 and outdoors. RH

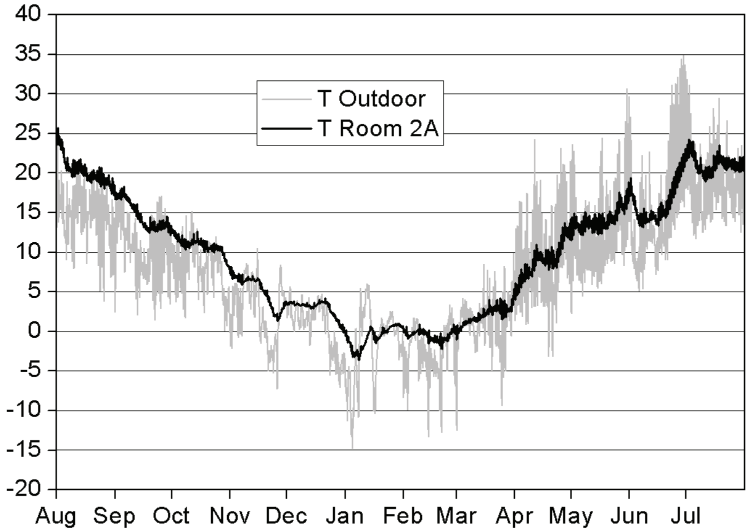

Fig. 4. T in room 2A compared to outdoors.

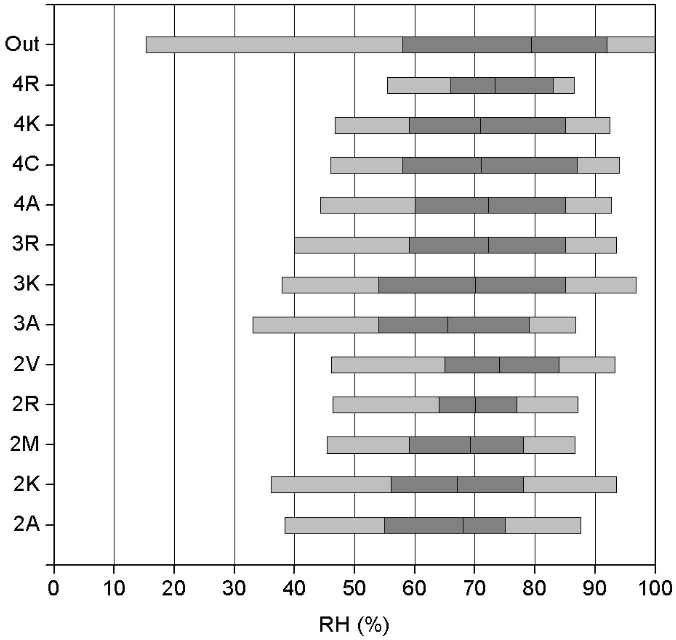

Fig. 5. RH in twelve selected rooms: seasonal range (light grey), range of 30 day moving average (dark grey). The line in the middle of each bar is the seasonal average.

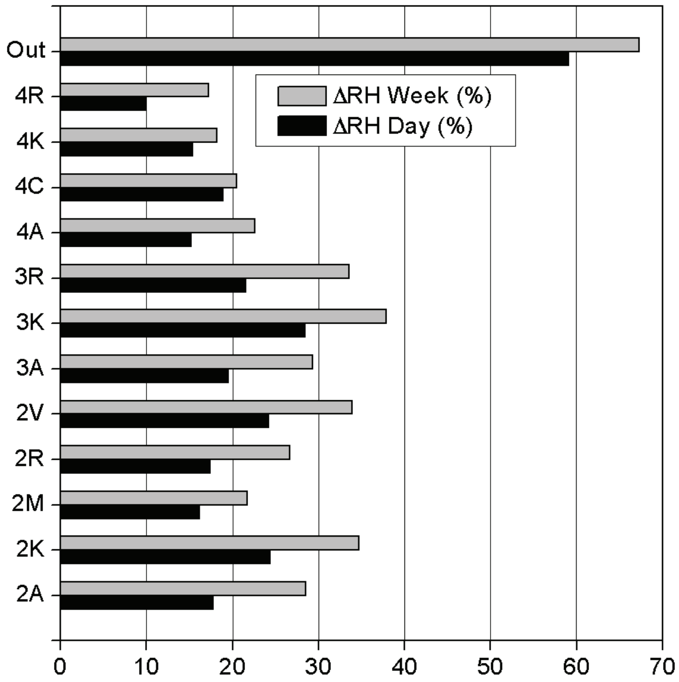

Fig. 6. Maximum variations in RH recorded for 24 hours and one week respectively during one year for 12 selected rooms.

is on an average 9 % lower inside than outside; the annual average RH of all rooms is 70 % as compared to 79 % outside. Going back to fig. 2 it can be seen that RH in the room is lower throughout the year. In the wintertime this is due to heat dissipating from the heated rooms on the first floor. In the summer, solar radiation is the most likely cause.

An analysis of the variations in RH confirms that the variations inside are reduced as compared to the outdoor climate and that there are considerable differences among the rooms.

The hourly values show that:

- For all rooms, the average seasonal variation inside is 48 % as compared to 85 % outside.
- The annual average RH among the rooms varies between 66 and 74 %.
- The minimum values of RH are in the range of 33 to 56 %, with an average among the rooms of 43% as compared to 15 % outside.
- The maximum values of RH are in the range of 87 to 97 %, with an average of 91 % as compared to 100 % outside.

In order to describe the seasonal variations, excluding the effect of short term variations, a moving 30 day average was used:

- The average seasonal variation among the rooms is 23 % as compared to 34 % outside.
- The minimum RH inside is in the range of 54 to 66 % with an average of 59 % as compared to 58 % outside.
- The maximum RH inside is in the range of 75 and 87 %, with an average of 82 % as compared to 92 % outside.

Fig. 6 shows maximum variations in RH for 24 hours and one week respectively during one year. The variations are remarkably high and there is a considerable difference among the rooms.

- The 24 hour variations are in the range of 10 – 28 %, with an average of 19 %, as compared to 59 % outside.
- The weekly variation is in the range of 17 – 38 %, with an average of 27 %, as compared to 67% outside.

Fig. 7 shows statistics for T for the 12 selected rooms.

- The average T of all rooms is 9,2 °C as compared to the outdoor average of 6,7 °C.
- Among the rooms the average T varies between 8,0 and 10,2 °C.
- The minimum values of T are in the range of -7,4 to -3,6 °C, with an average of -5,5 as compared to -15 °C outside.
- The maximum values of T are in the range of 23 to 29 °C, with an average of 25 as compared to 35 °C outside.

Fig. 8 shows statistics for AH in the 12 rooms.

- The average AH of all rooms is 6,6 g/m^3 as compared to the outdoor average of 6,3 g/m^3.
- Among the rooms the average AH varies between 6,5 and 6,8 g/m^3.
- The minimum values of AH are in the range of 1,7 to 2,0 as compared to 1,5 g/m^3 outdoors.
- The maximum values of AH are in the range of 13,2 to 14,2 g/m^3 as compared to 15,9 g/m^3 outdoors.

As compared to other masonry buildings in the region, the moisture surplus, in terms of AH, in the building is low. This would indicate that there is very little moisture added to the building from the ground or driving rain in relation to the air exchange.

The graphs above show that there are significant differences in the indoor climate among the rooms. Table 1 shows average values for January and July in the 12 rooms, divided by floor and orientation. Rooms facing south are slightly warmer, resulting in a

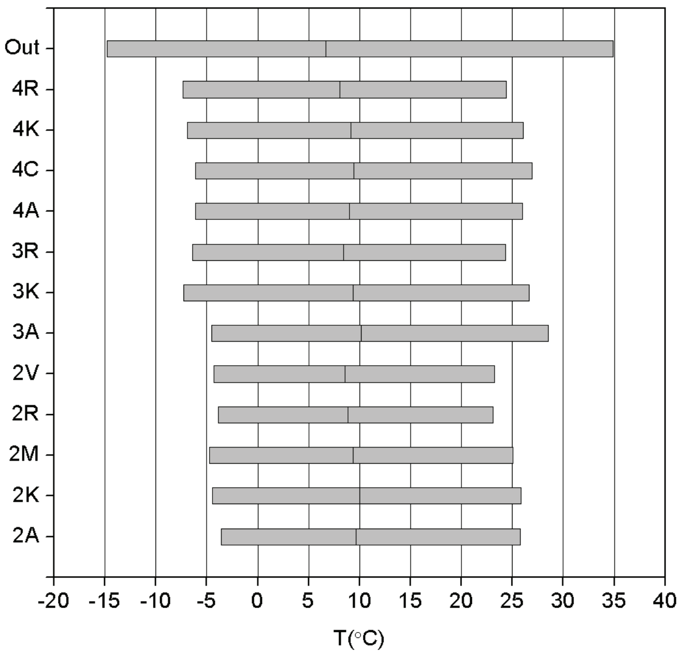

Fig. 7. The seasonal range of T in twelve selected rooms. The line in the middle of each bar is the seasonal average

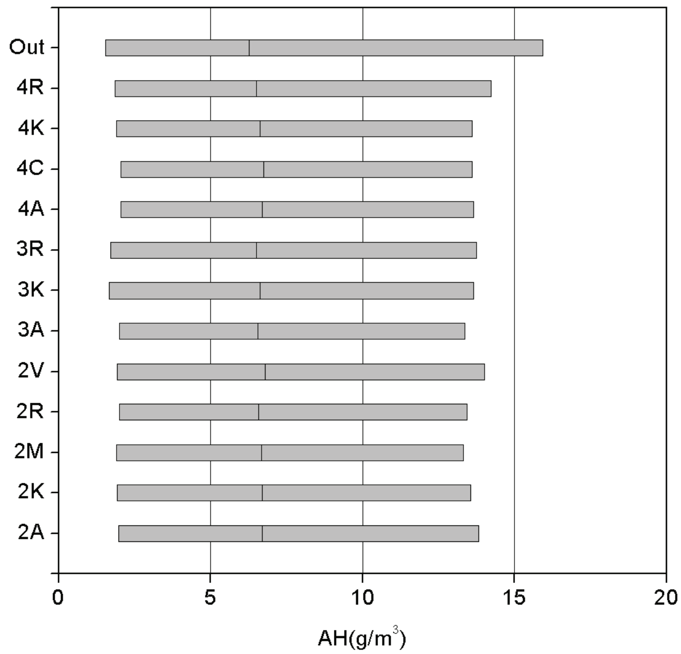

Fig. 8. The seasonal range of AH in twelve selected rooms. The line in the middle of each bar is the seasonal average.

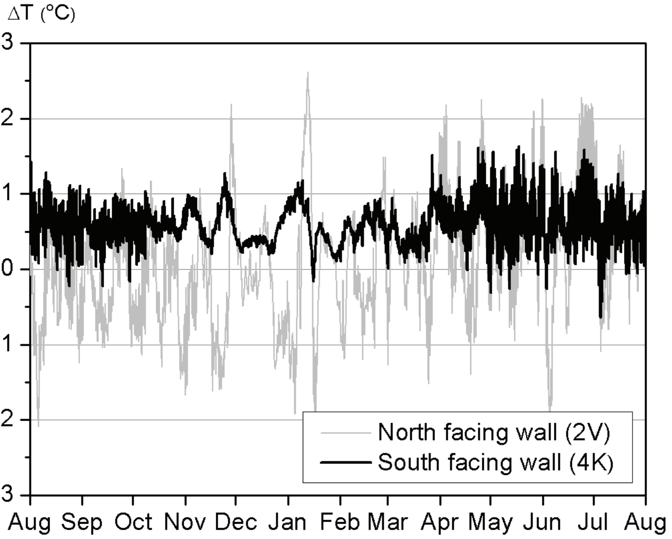

Fig. 9. Temperature differences between wall and room air on a north facing wall in room 2V and on a south facing wall in room 4K.

lower RH in the summer but not in the winter. In the winter the second floor is slightly warmer and drier than the other due to heat dissipating from the heated rooms on the first floor. During the winter, the average temperature on the third and fourth floors are practically the same as the outdoor temperature. In the summer the indoor temperatures are significantly higher than outdoors.

	January		**July**	
	RH (%)	T (°C)	RH (%)	T (°C)
Facing south	80	-1,1	60	21,9
Facing north	80	-1,9	65	20,7
2nd floor	77	-0,9	65	20,8
3rd floor	81	-1,7	60	21,7
4th floor	83	-1,9	63	21,0
Outdoors	88	-1,8	73	18,7

Table 1. Average RH and T during January and July.

Horizontal gradients were measured in rooms 2A and 2R. Within the rooms, the microclimate was rather homogeneous throughout the year, with a maximum temperature difference (ΔT) of less than 0,5 °C, and with no significant difference of AH.

Surface T on the inside of exterior walls has been measured in five rooms. ΔT between the wall and air were generally small. The differences in a south-facing room (4K) and a north-facing room (2V) are shown in figure 9. In the north facing room the average wall surface temperature was 0,6 °C lower than the average room air temperature. For the south facing room there was no difference in the average temperatures of wall and air. In both rooms, ΔT stays within ±1°C most of the time. ΔT was more stable over the year on the north side than on the south side.

The air change rate per hour, ACH was measured in room 2A and room 3R during four periods. The results are shown in table 2 Outdoor average wind speed and the temperature difference between indoor and outdoor are also presented as these are the main driving forces for the infiltration. Room 2A has a volume of 530 m^3, 3R 350 m^3.

The ACH in both rooms is in the range of 0,4- 0,6. Measurements in adjacent rooms confirm that the overall ACH in rooms on the first and second floor at Skokloster are around 0,5 with the exception that rooms in the corner towers have a much larger ACH. There is not enough data to establish a general correla-

Period	**Jul 08**	**Oct/ Nov 08**	**Feb 09**	**Apr/ May 09**
ACH 2A	**0,45**	**0,40**	**0,46**	**0,46**
± ACH 2A	0,03	0,02	0,03	0,04
ACH 3R	**0,52**	**0,44**	**0,62**	**0,62**
± ACH 3R	0,04	0,03	0,04	0,04
ΔT (°C)	4,1	1,4	2,1	3,1
Wind (m/s)	3,0	3,8	2,4	3,2

Table 2. Air Change Rate per Hour in room 2A and 3R. ΔT is the mean difference between the temperatures in the rooms and the outdoor temperature. Wind is the average wind speed over the period.

tion between air exchange and the variations in the indoor climate. This will be the subject of a future study, with the use of air exchange data from more rooms.

4. Risk assessment

In the following we will identify and assess risks to the collection and the building based on the description of the indoor climate. The objective is to indicate in which direction the indoor climate should be improved to reduce or eliminate the primary risks.

We have deliberately not based the analysis on the state of the collection or the ongoing decay of individual artefacts. This makes a quantitative risk assessment based on a prediction of the loss of value to the collection impossible [1]. Nevertheless, given the mixed nature of the collection, we believe that estimates about the magnitude of risks can be made based on general knowledge of deterioration mechanisms.

Conventionally, the basic procedure for evaluating the indoor climate is to use a standard. However, the present indoor climate is beyond even the most relaxed standard used today for indoor climate in museums, the ASHRAE Class D [2], with the only requirement that RH is below 75 %. In order to identify the potential for improvement of the present indoor climate, we will discuss biological, chemical and mechanical decay.

The primary consideration is to avoid mould growth. Whereas mould not always causes material damage, the health aspects and visual impact could eventually render the building unfit as a museum. In addition to this, the cost of removing mould is so high that preventive measures are always a good investment. The three major parameters governing mould growth are RH, T and time. Fortunately, the very high RH during winter is combined with a low T that reduces the risk for growth. Each room has been analyzed with so called isoplets defined by Sedlbauer[3], (fig 10). A drawback with this approach is that the influence of dynamic conditions is not considered. During the present period of measurements, only two rooms showed a high or very high risk for mould growth. However, the climate in many rooms is close to the risk zone almost all year round, and a small change in the outdoor climate could move them into the risk zone. This is clearly a substantial risk to the collection, and it is necessary to avoid the combination of RH and T in the risk zone.

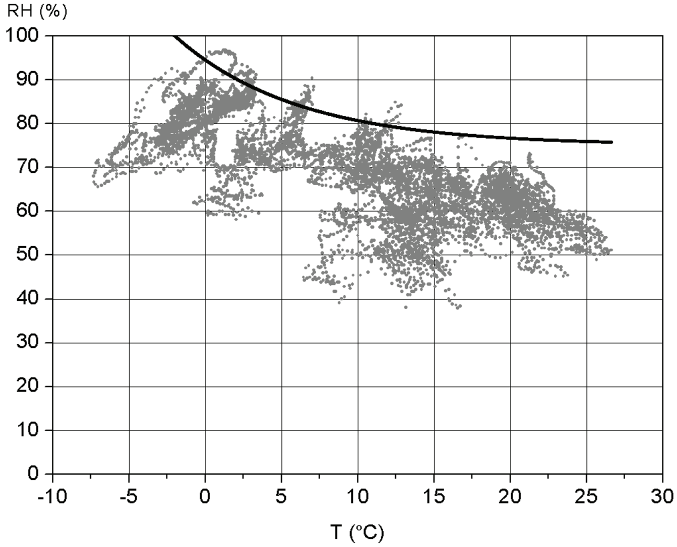

Fig 10: RH and T in room 3K. The area above the curve is the risk zone for mould growth-

Chemical degradation increases at high RH and decreases at low T. For some chemical reactions, such as metal corrosion and glass deterioration, high RH-levels are critical. Therefore, a general advice would be to reduce the high RH-values, even if it is difficult to assess the magnitude of this risk.

Mechanical degradation is due to fluctuations in RH and, to a lesser extent, T. A key question is how to take into account the rate of change, i.e. how to define the duration of long and short term variations. The average seasonal variation of the 30-day moving average of RH is 23 %; at the same time we find 24 hour variations that exceed this range in many rooms. It would be possible to assess the risks for each individual object by determining its mechanical response, and define the time constant based on the properties of the objects. In most cases this is not a realistic option. An interesting alternative is to use the concept of "proofed fluctuations" [4]. Most of the artefacts have been exposed to almost the same indoor climate for centuries. Plastic deformation and failure have occurred in many objects and these structural changes now act as expansion joints that reduce the stress levels. This does not mean that the decay has stopped and that the objects are safe, but suggests that as long as the variations do not exceed the historic levels, the risk for further damage is low. As a general safety measure in order to achieve this, both long and short term variations of RH should be reduced. There are reasons to achieve this reduction by lowering the upper limit. Firstly, the coefficient of expansion for most hygroscopic materials increases with increasing RH. This has a dramatic impact on the tolerable range of fluctuations. Secondly, many materials change their material properties in the high humidity region and become more susceptible to damage [5].

Even though the winter 2008-2009 was mild, all of the rooms had temperatures below 0 °C. This may very well be below the glass transition temperature for traditional oil paints, varnishes, lacquers and the like. This is not damaging in itself, but the paint film becomes brittle and is therefore susceptible to forces from handling or fluctuations. The brittleness in combination with the high humidity level and the short term RH fluctuations during winter constitute a risk for the painted objects. This is an area where further investigations are needed to gain a better understanding the risks.

In conclusion, these are the general directions for the improvement of the indoor climate with respect to preservation:

- Control T and RH to avoid mould growth.
- Reduce the high RH-levels.
- Reduce both seasonal and short term variations in RH

Reduce the prevalence of very low temperatures in combination with fluctuations in the high humidity range.

5. Interventions

Given that there is practically no active climate control in the building, the indoor climate is governed by:

- The outdoor climate as a driving force:
    - Temperature
    - RH
    - Wind
    - Solar radiation
- The building envelope as a moderating force:
    - Insulation
    - Air tightness
    - Hygrothermal buffering
- Other factors influencing the indoor climate are:
    - The location of the rooms: orientation and floor
    - The use of the building as documented in the log book

Given the long tradition without active climate control in Skokloster castle, the primary option is to reduce the influence of the outdoor climate by enhancing the passive function of the building. As a secondary, and at this stage hypothetical option, active climate control will be considered.

5.1. Reduce seasonal variations in RH

The large RH variations over the year can be attributed to short-term variations superimposed on seasonal variations. The seasonal variations based on the 30 day moving average, are modest with an average value of 23 %. The range of variations among the rooms is 13 – 31 %. This suggests that there is a potential to reduce seasonal variations in most of the rooms. These differences between the rooms can be explained in terms of heat input, air exchange and buffering capacity.

The duration graph below (fig. 11) shows the distribution of RH for rooms on floor 2 and 4 in relation to outdoor values. The slight difference between the rooms has a dramatic effect on the duration. In the room on the second floor RH exceeds 80 % for around 500 hours as compared to 2 500 hours in the upper room. The same numbers for the 70 % level are 3 500 and 4 500 hours respectively. If conservation heating or dehumidification were to be used to reduce the most extreme values of RH, the operation time would vary considerable with the target level and between the rooms.

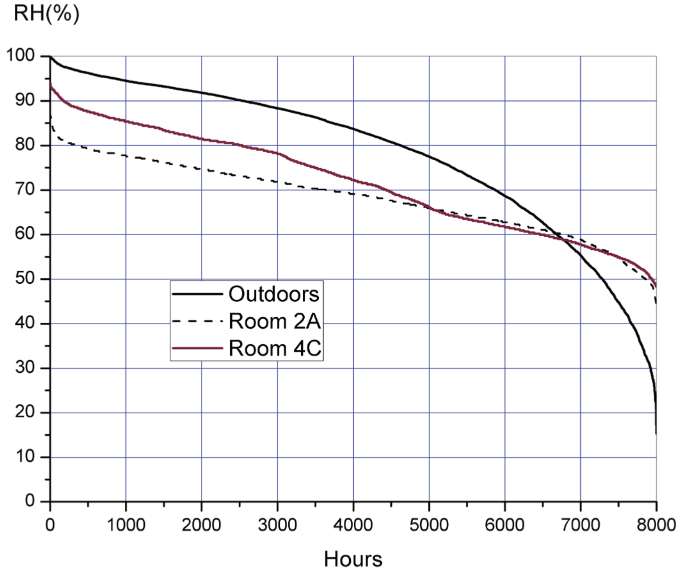

Fig. 11. Duration graph for RH in selected rooms on floors 2 and 4 as compared to outdoor values.

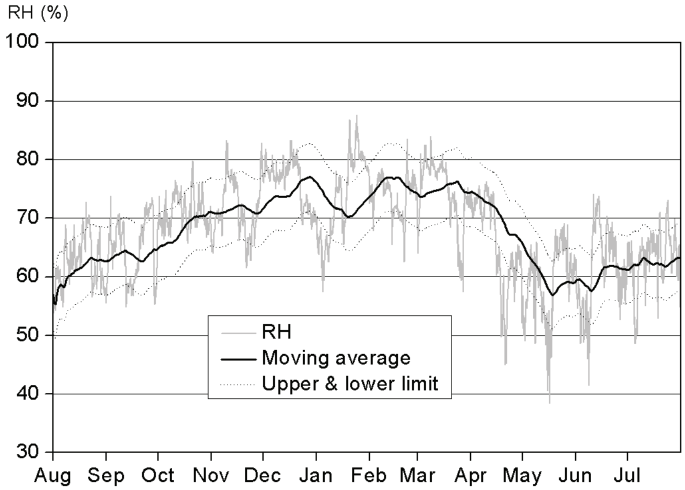

Fig. 12. RH hourly values, moving 30 day average and target range for room 2A.

5.2. Reduce short term variations in RH

In order to assess the short term variations and identify extreme events we have used an approach proposed by Bratasz et al to determine a target range for RH based on the climate history of a specific building [6]. The mean target value for RH is calculated as a moving average over a 30 day period, from measurements for at least one year. The aim is to identify harmful fluctuations in relation to the seasonal average. A fluctuation from the seasonal average is considered outside the safe range when the magnitude is more than one standard deviation.

The result of this analysis was carried out for room 2A as shown in fig. 12. All the events that deviate from the target range were analysed. It was concluded that all deviations can be explained from variations in the outdoor climate. Variations in T, AH and wind speed would separately cause the RH to vary inside. A combination of them causes the most extreme variations. There were no extreme events that seemed to be caused by the use of the building or any active interventions according to the log book. Most of the events are of longer duration than 24 hours, but there are also diurnal variations outside of the target range.

The range of variations among the rooms (fig. 5 and 6) indicates a potential to reduce short term variations by passive measures only. A realistic target would be to reduce the high levels and variations in RH to the levels for the best rooms:

- Maximum value: <85%
- Seasonal variation: <35%
- 24 hour variation <15%
- Weekly variation <20%

5.3. Reduce the prevalence of very low temperatures in combination with fluctuations in the high humidity range.

By reducing air exchange, as suggested above, the effective thermal buffering will increase. Reduced air exchange should eliminate the extreme values, but in order to raise winter temperatures inside the castle, heating is the only option. Fig. 13 shows the duration of temperatures in room 2A. To keep room T above 0 °C throughout the year would require heating for around 1000 hours. Conservation heating would of course also reduce RH.

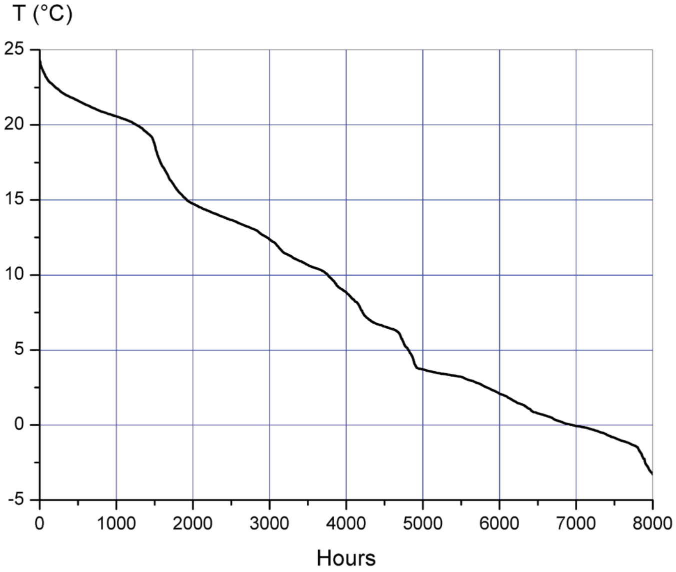

Fig. 13. Duration of temperature for room 2A.

5.4. Control T and RH to avoid mould growth.

The main challenge for preventing mould growth is to come up with a truly proactive system but yet appropriate in terms of costs and technical complexity. Once the problem has been detected it is too late. Controlling the air exchange, as discussed below, will reduce the influence of unfavorable short term variations that would otherwise move the indoor climate into the risk zone. On the other hand, more stable conditions might increase the rate of growth within the risk zone [7]. In room 3K, (fig. 10), the highest risk for mould growth occurs between October and April at relatively low temperatures; below 10°C. In this regime, conservation heating would be an efficient countermeasure. Unfortunately, most rooms investigated are uncomfortably close to the risk zone throughout the whole year. Experience tells us that conservation heating in the summer is not acceptable in public buildings. Dehumidification in combination with controlling the air exchange would be the recommended option in the summer.

As the climate within the rooms is quite homogeneous risks associated with microclimates in corners, behind paintings and furniture etc. are less than in heated buildings.

5.5. Controlling air exchange

Given the limited use of the building, ventilation for comfort is not a primary concern. During events with many visitors, which would occur mostly in the summer, air exchange can be increased by opening windows and doors.

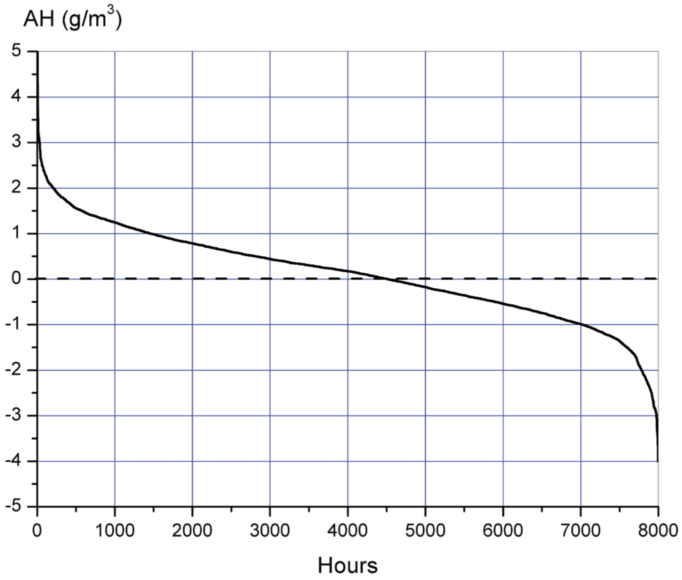

Fig. 14. Duration for the difference in AH between the inside and outside.

In order to reduce variations in indoor climate, we can reduce air exchange. This is a strategy that has been used with good results in museum stores [8,9]. The air exchange in the castle is moderate as compared to other historic buildings, but it could be further reduced by closing vents and improving air tightness of windows and doors. It should be noted that the flue pipes of all stoves have been kept open throughout the period of measurement.

On important aspect to consider is whether reduced ventilation would increase the risk for mould growth. On an average over a year, AH is practically the same inside as outside. The average value inside is in the range 6,3 – 6,6 g/m^3 as compared to 6,4 g/m^3 outside. This suggests that there are no significant moisture sources inside. Some rooms have been exposed to moisture from leaking roofs and they will need continued air exchange on the present level. Given the complexity of the matters and the high risks, one should proceed carefully.

Moisture controlled ventilation has been tried in historic buildings and museum stores [10]. Whenever AH is lower outside than inside, the ventilation is turned on. Fig. 14 shows the duration for difference in AH. When the value is positive, ventilation will reduce AH in the building and vice versa. The driving force, expressed in difference of AH, is generally quite low, less than 1,0 g/m^3 most of the time. The difference in AH varies over the short term so there is no seasonal pattern that would motivate manual interventions by opening doors, flue pipes etc.

6. Conclusions and discussion

On the general issue of using historic buildings as museums, we don't see any major climatic problems in Skokloster castle related to the visitors. The question is rather how well the building is suited to house the objects and what can be done to improve the preservation conditions.

The climate measurements and the risk assessment identified four general targets:

1. Control T and RH to avoid mould growth
2. Reduce high RH levels
3. Reduce variations in RH
4. Reduce the prevalence of low temperatures

The basic strategy for controlling the indoor climate in a museum store should be to minimize the disturbances from the outdoor climate through the passive function of the building envelope.

The different behavior among the rooms indicates that the variations in RH can be reduced by enhancing the effective hygrothermal inertia of the building through a reduction of the air exchange. In a second step of investigations this hypothesis will be tested.

In order to substantially reduce the mould risk temporary conservation heating and/or dehumidification is needed. Given the long history without active climate control, an in depth risk assessment must be made before such measures can be proposed. In a forthcoming investigation, the risk for mould growth in relation to the variability of the indoor climate will be studied, based on more refined methods [11,12]. Also a systematic damage inventory will be made to investigate the extent of mechanical damage related to high RH and low T.

Looking at the operative process dealt with in the present paper; *measurements – risk assessment – interventions*, it is clear that risk assessment is the weak link. A qualitative assessment allows us to change the climate in the right direction, but we are very far away from any kind of cost-benefit analysis. Furthermore we need standards to describe and analyze the indoor climate as an input to risk assessment. Finally, the engineers need tools to assess load for various types of climate control. The duration graphs presented in this paper are one step in that direction.

In relation to commonly used standards and guidelines for historic buildings and/or museum stores, the indoor climate in Skokloster appears to be problematic. However since the state of preservation is better than the climate would suggest, Skokloster serves as an interesting example of sustainable climate management in terms of allowable ranges, building properties and passive control.

7. Acknowledgement

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Paper IV.

Rethinking indoor climate control in historic buildings: The importance of negotiated priorities and discursive hegemony at a Swedish museum

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Abstract

Much effort has in recent years been directed to support sustainable indoor climate control strategies in historic buildings. In this paper we show the necessity to complement the dominant technical approaches with research that take a wider interest in specific contexts, social practices, and negotiated decisions. The objective of the paper is to illustrate how the interactions between perceptions and experiences of different professional groups are pivotal for the management of the indoor climate. An ethnographic study of decision making in an historic house museum was carried out in 2009 and 2012. Interviews were made with individuals who either took part in management or were affected by the indoor climate. The findings show how discussions among social actors and the way their respective priorities are negotiated are essential features of the management of the indoor climate and have a strong impact on the ability to modify it. It turns out that a hegemonic discourse about preservation as the dominant rationale for indoor climate control in tandem with "acceptable" conditions with respect to preservation have reinforced a state of stability. This explorative study opens up for a re-framing of how a more sustainable management of historic buildings can be achieved.

Keywords

Environmental management; decision making; practices, preventive conservation

1. Introduction

With a long-term perspective there is much in favour of a shift toward indoor climate control strategies which use less energy and thereby also are robust to a range of possible future developments. Uncertainty regarding future energy prices and the societal goal of reducing greenhouse gas emissions from buildings are factors that make a transition toward low-energy solutions an important goal for both practice and policy.

Decisions concerning indoor climate control tend to revolve around two basic questions: What type of indoor climate is preferred and how can it be achieved? However, particularly for historic buildings housing valuable collections, these questions are at the crossroads of conflicting objectives regarding the use and preservation of the building and the collection. Furthermore, they often turn out to be complicated to deal with in practice, despite a plethora of guidelines [1]. Diffuse power relations between different professional groups (e.g. architects, conservators, engineers), and the interdisciplinary nature of the problems involved, make indoor climate control an intriguing challenge which goes beyond techno-economic analyses. With this paper, we present a complementary perspective to the discussion on how indoor climate control in historic buildings housing valuable collections can be made more environmentally sustainable.

Researchers and practitioners have generally perceived the issue of indoor climate control in historic buildings through a technical lens, focusing on aspects such as how the indoor climate affects the deterioration of materials [2].One dominant task for scientists has been to identify dangerous thresholds for different parameters, especially temperature and relative humidity of which the latter is crucial for preservation [3]. Another has been to investigate how technical innovations may be used to avoid these thresholds e.g.[4]. Scientific results from these areas of expertise have been assumed to support key decision-makers, such as collection managers, to make informed and rational decisions about indoor climate control.

The way in which expert knowledge has been shared has shifted in parallel with the development of preventive conservation. Attempts to guide collection managers on indoor climate control used to come in the form of guidelines, handbooks and standards suggesting universal numbers for different parameters. This approach was based on precaution and what was considered possible to achieve with best practices [5]. More recently there has been a tendency toward risk based approaches which acknowledge significant problems connected with the notion of an "ideal climate" [6,7]. The most recent development in standardization opens up for a wide range of strategic choice - the advice given essentially provides a framework for a risk based decision process [8].

Despite the fact that the attempts to give advice to decision-makers about indoor climate control have differed widely in terms of scope, sophistication and scientific backing [9,10], we argue that they have been grounded in an understanding that fits with Hendry's [11] account of "the traditional perspective" on strategic decision making. Decisions are conceptually unproblematic in this perspective. They are seen as the output of attempts at rational choice, and as something which form the main basis for strategic action. However, several studies have shown that decision processes in organizations can hardly be understood in terms of the traditional perspective [11,12]. Not only are decisions hard to pin down empirically, their relationships to other constructs such as choice, determination and action are far from the ready-made account suggested by normative decision theory [11–13]. Given that the literature on indoor climate control for collections is foremost technical or normative, it should come as no surprise that it tends to be based on the traditional, presumably rational, account of how decisions are made and actions come about.

Social scientists have suggested that the failure of energy reduction policies can be tied to a simplistic understanding of energy users, characterized as purposive and rational individuals or organizations [14]. It has further been argued for a widening of such techno-economic perspectives on energy users, with an emphasis on the importance of considering how practices are shaped, adjusted or recreated among and between organizations, professional groups, and other social actors e.g. [14–18]. Moezzi and Janda [19] have discussed a notion of 'social potential' for energy savings as a strategy which is not restricted to untapped 'technical potentials', largely focused on how to get people to buy energy efficient things, or to the untapped 'behavioural potentials' supposedly found in individual consumption, choice-making, or life style. Rather, the 'social potential' give credit to the fact that social groups have enabling, mediating and aggregating functions which affect other actors in meaningful ways.

In social practice, differing goals tend to be incompatible to varying degrees [20,21]. Thus, in a specific context and situation, one goal may be considered more legitimate than another, and one actor may have more to say on a certain decision than another. Different goals may be negotiated, fought about, or simply ignored or played down. We focus here on situations when individuals, who represent different organizations or professional groups, need to collaborate in a setting where claims of knowledge are contested and power relations are diffuse.

Each relevant social actor carries culturally embedded pre-understandings of certain situations of choice and decision making. For each individual or professional group, choices are framed, not only by their varying roles and responsibilities, but by varying experiences, and horizons of perceptions and expectations [13]. Consequently, when decisions evolve through interaction within or between organizations or professional groups, the varying perceptions and practices need to be considered in each particular case. We therefore suggest, in accordance with Berkhout [22], that organizations should be analysed with an inside-out rather than an outside-in approach, and take as a point of departure the complex reality of the organization itself. Based on the above, we argue that a wider interest in specific contexts, social practices, and negotiated decisions is a necessary prerequisite for understanding the emergence, stabilization and change of indoor climate control practices, and, in the end, to inform policy-making.

Even though we, in this paper, do not pay specific attention to the building itself, nor to the art collections and immovable interiors within, these are intrinsically linked to the professional groups we describe, as well as to their respective tasks, perspectives and priorities. A recent article by Walker, Shove and Brown [23] shows some similarities to ours in that respect, although their aim is to illustrate the growth of a perceived need for more air conditioning. A case study at a hospital in Northern UK illustrates, in their article, how buildings are not merely the locus of ongoing practices, but also materially bound up in those practices. ‘Building project dynamics’, they say, ‘are to a significant degree subject to what goes on within them’ [23].

The objective of this paper is to use a case study to illustrate, in some detail, how the interaction between perceptions and experiences of different professional groups are pivotal factors for the management of the indoor climate in heritage buildings. Rather than exploring how unsustainable practices emerge and evolve, as in the cited study of air conditioners, we here use a case of stability. To understand why such stability occurs and how it is sustained is essential for how, and to what extent, changes towards more environmentally sustainable indoor climate control strategies can be achieved.

2. The case study

As case study, we have chosen a large historic house museum in Sweden, a building of medieval origin. As a state-owned monument, the building, as well as the collections within it, has plenty of resources in terms of money and know-how for issues related to preservation.

The museum was chosen for this study partly because of its complex management structure. Separate organizations, in this paper called B, C1 and C2, are responsible for different aspects of the conservation of the building and collections. Organization B is responsible for the building and its immovable interior, C1 for most of the movable objects such as furniture, and C2 for a large collection of paintings. C1 and C2 share the responsibility for the visiting services. These organizations differ in their claims and responsibilities regarding indoor climate control. The explicit use of a multi-disciplinary team of professionals for decision making about indoor climate control in the museum makes it an interesting case to investigate, especially concerning processes of negotiation and collaboration.

3. Methods

In order to gain a better understanding of the varying perspectives concerning the indoor climate control of the museum, a number of semi-structured interviews were carried out in 2009, with one complementary interview made in 2012. Each interview lasted between one and three hours. The aim was to interview individuals at each level of management. All the interviewees either took part in decision making concerning the indoor climate or were affected by it in some way. The size of the staff varies throughout the year and it also depends on how much conservation work that is going on. The permanent staff that had the visitor areas as their main place of duty during the whole year (all except one housekeeper) was interviewed as well as the individuals in the managing organizations which were mostly involved in indoor climate issues. In total, eleven individuals were interviewed:

Organization B: two building managers and one indoor climate specialist.

Organization C1: two conservators, one curator, two guides and one housekeeper.

Organization C2: one conservator.

Minutes of meetings from the preservation group and archival records have been used as complementary sources of information. The interviews revolved around how the interviewees perceived their and other actors' roles in relation to the indoor climate. One central issue was how they described and related to the current indoor climate and the technical equipment for control, another was their opinion on how decisions about indoor climate control were made and how they perceived their own and others' influence on this process.

4. The growth of an indoor climate control strategy

The building has an interesting history of indoor climate control with respect to preservation. A heating system was installed in the late 1920´s to lower the humidity. The system comprised electric resistance heaters installed inside existing fireplaces and tiled stoves. The heating was to be turned on in the evening with a central switch in order to use the low tariff during the night. There was a constant power output and no temperature control, except the possibility of shortening the heating time during night. Experiments had shown that the installed power would increase the indoor temperature to around ten degrees above the outdoor temperature. The heating season was supposed to start either when the indoor temperature fell below +4 degrees or when the relative humidity exceeded 85 %. During the course of time the radiators have been supplemented with individual thermostats. The current control regime states that the radiators should be turned on in October. The temperature setting is 10-12 degrees, but each thermostat has to be fine-tuned in order to achieve this level in the room. The same setting is then used throughout winter until the radiators are turned off in May.

In 2005 a project was initiated with the aim of investigating the indoor climate. The investigation was conducted by a consultant in collaboration with one of the conservators. Temperature, relative humidity, and UV-radiation were monitored. Although the indoor climate was reported as acceptable in relation to preservation in the final report, a few problems with the indoor climate were identified. The constant temperature setting was reported to cause a seasonal fluctuation of relative humidity, with too low values during winter. Gradients of temperature and relative humidity within the building were also described as problematic. To solve these problems, it was suggested that the temperature should be centrally controlled to a temperature of six degrees above the outdoor temperature, in the range of 8-18 ºC. This suggestion was never realized due to a conflict regarding thermal comfort for the staff. Another suggestion was that a ‘preservation group’ should be formed, where representatives from the different organizations could discuss issues related to preventive conservation. This suggestion was realized and a group was constituted, consisting of the three organizations with varying responsibilities towards the museum building and its historic collections. Even though these organizations were continuously represented in the preservation group, the individuals who represented them varied over the studied period.

The core group included the two interviewed building managers from B and one conservator from C1 and C2 respectively. The guides and housekeepers were represented in the preservation group only by their employer, who attended the meetings intermittently.

5. Perspectives on the indoor climate

When all interviewees are taken into account (also those who have little saying and do not themselves attend the preservation group), it becomes clear that, among the professional groups, there are some very different ways of relating to the building’s indoor climate. Responsibilities and ability to have an influence differ, as do their respective embodied experiences and the amount of time they tend to spend at the museum.

For instance, the *building managers*, who share the overall responsibility for the building, make regular visits to the museum but do not spend extensive periods there. The *conservators* from C1 are working in the museum part time depending on the workload, while the conservators and curator from C2 spend less time in the museum. They generally make visits in the spring to “open” the collection for the summer season, and in the autumn to “close” it. The *guides and housekeeper* have the museum as their daily work place all year round, but have few options to have an impact on the indoor climate.

The following section explores ways by which interviewees experience the indoor climate, as well as how they feel responsible for, and give priority to, different aspects of indoor climate control. The section is structured around the three most salient indoor climate issues that emerged during the interview analysis: preservation, comfort, and energy. These issues also constitute the three dominating rationales for the extent of indoor climate control.

5.1. Preservation – keeping status quo

One of the conservators from organization C2 is more involved in the control and monitoring of the indoor climate than the others. This conservator seems to be the person who is most “in charge” of the indoor climate of the museum, although this is not an official responsibility; she represents the interests of organization C2 only. For her it is clear that the preservation aspect of the indoor climate is the overarching priority. Still, even though she states that the indoor climate is generally good with respect to preservation, she is also of the opinion that the current indoor climate control system is not entirely unproblematic, and that there is no comprehensive picture.

The conservator describes several problems with the current indoor climate. The old thermostats do not allow for any fine-tuning of the temperature, and there are temperature and humidity gradients both within and between rooms partly because of this. Consequently, there have been problems with condensation on textiles in some rooms during mild autumns, and during cold winter periods it can become too dry. The high humidity in some rooms is also thought of as contributing to increased problems with pests. It is also problematic that the relative humidity becomes higher in some rooms where the unheated period is extended. The background to this is that it takes time to vacuum all the unshielded radiators that have collected dust during summer, something which has to be done since dust is a fire hazard and add to the soiling of surfaces.

The conservator describes two previous unsuccessful attempts to adjust the current system. One concerned a replacement of the thermostats which stranded due to technical problems. The other was the cancelled attempt to lower the winter temperature to a minimum of eight degrees, mentioned above in section 4. These disappointing experiences, in combination with a lack of time, have discouraged this conservator from further efforts to improve the existing climate control system. Most of her time is now spent on acute problem-solving, and the strategic work is limited to a few dedicated projects, such as risk assessment of a storage facility and the introduction of a new climate control system in a previously unheated part of the museum.

The building managers, on their hand, work closely together with the management of the building and they both regard preservation of the building fabric as their main responsibility. They seem to share an understanding that the heating system has worked well throughout the years. From their perspective it is evident that, despite some minor problems, the present heating strategy has proved to be good for the preservation of the building fabric.

One of the building managers refers to similar buildings which have suffered from problems related to new technical systems. He goes on to state that even though the present system is not the optimal one, it is acceptable and has proven to be good for the building in the long run:

> I think it is very dangerous to start experimenting with the indoor climate without knowing what you end up with… first you do one thing to improve something else and then you have started a chain reaction and you never know what to do in the end. […] [the indoor climate control system] does not need to be good, it should be acceptable and we ought to be rather satisfied if we make an old building acceptable

> in this respect, both concerning energy use and climate and other things… if you find that balance you have come a fairly long way. (Building manager)

His colleague shares this view and argues that with current priorities there are reasons to doubt if a change would be beneficial:

> Yes, we could make [the control of the radiators] even better… /…/ make this relative humidity curve even tighter, this range that we can accept. But then is the question, and that is a matter of discussion, how much is gained from something like that? The energy issue has not been a matter of concern; it is the indoor climate for preservation and relative humidity that we have discussed [in the preservation group]. The question is how much better it will be and that is something we don´t know and still it is acceptable as it is now, there is nothing that is directly damaged as it is now, except in the [unheated part], where it is totally uncontrolled. (Building manager)

In addition to having the responsibility for the preservation of the building fabric, one of the building managers is also responsible for how the building is displayed to visitors and how interventions are carried out. This includes decisions on lighting, new installations etc. Since the appearance of the building to visitors is paramount for him, he is satisfied with the limited visual impact of the present heating system. According to him, a new hot-water heating system is out of the question both from a visual and a physical point of view.

Among the guides and housekeepers, there is a common understanding that the climate is controlled with the aim to improve preservation, and that other aims are more or less disregarded. However, in general, they do not seem to be well informed about how the indoor climate affects deterioration, or the rationale for the current heating regime. On the question of why twelve degrees has been chosen as set point, one of the guides answers that he is not really sure, that it is related to humidity but concludes that this knowledge is not communicated. He expresses a lack of involvement and that the discussion is taking place above his head.

Preservation, both of the building and the collection, is clearly the dominating rationale for indoor climate control. The different arguments laid out above reveal subtle, but important differences in how the various professional groups interpret the means and ends of cultural heritage management and how they rationalize their respective positions. The building managers focus on the well-being of the building as a whole and on avoiding irreversible changes from new installations. They base their judgments foremost on the track record of the existing heating system, which they compare to less successful attempts at other sites. One of the building managers is also focused on the experiential values of the building and the present system is favourable in that respect. The conservators pay, in comparison, more attention to damage at the micro level and show less interest in experiential values. They can imagine possible improvements with respect to preservation but lay out several arguments for why they are not pursuing a change. The guides and housekeepers, for their part, play an important role for preservation but their understanding about the role of the indoor climate is rather vague.

5.2. Comfort – embodied experiences

The varying perceptions of what constitutes a problem are also related to the differing embodied experiences that are built into the various professional practices. The comfort issue shows how the indoor climate is experienced, understood and communicated in completely different ways depending on whether one work in the museum building or not. Among those who have the museum as their daily work place, the current thermal comfort is considered unacceptable. Their ability to cope with the low temperature is also seen as limited due to factors as diverse as a malfunctioning technical system and expectations of 'appropriate clothing'. A quite contrary view is found among those who only make occasional visits to the museum. For them, the current thermal comfort is acceptable, and the ability to cope with the low temperature during winter is perceived more as a matter of individual adaptation.

Among guides and housekeepers, it is a daily, routine activity to experience and relate to the indoor climate. It is a reference point for small talk and central for activities, such as preparing for a work session in the castle by putting on warm clothing or regaining heat when work is finished. The staff working in the museum generally thinks that the present system performs poorly in terms of thermal comfort. In focus is the low general temperature level during winter, which makes sedentary work, such as some cleaning tasks, difficult to cope with.

> If you are to stand still and work /…/ some areas are to be considered as dangerous to one's health, this is something that has gotten worse with age. (Guide)

The housekeeper describes how she is hypothermic after a full day working in the museum during winter and how it "takes hours to thaw out after I have arrived at home".

Apart from the low temperature level during winter, there is a general concern among the guides and housekeepers that the control system is outdated and technically malfunctioning. One of the guides says that "the thermostats do not work well, the set point can be 8 degrees but it is still 18 degrees in the room". They say that you clearly can feel the difference in temperature between rooms you walk through during the heating season. The seasonal change is also noticed: "In the reception it is terribly cold. October is worst, it is cold and humid." Sometimes it happens that someone who feels cold changes the thermostat setting in a room without permission.

The dress code for the staff in the museum is considered problematic in terms of thermal comfort. It is important for the staff to look neat and tidy when there are visitors around, a fact that limits the possibility of putting on warm enough clothing. There is no official dress code, but there is a strong informal one.

Also the conservator from C2 spends a lot of time working in the museum, and is concerned about the thermal comfort – it is often very cold. Still, she considers this to be a feature of these kinds of buildings and a part of the job which she has accepted.

Contrary to the guides, housekeepers and some of the conservators, the building managers perceive the indoor climate from a physical distance as they do not have the museum as their daily workplace. They describe the thermal comfort in terms of a necessity which is as much dependent on the staff as the actual indoor climate:

> …for sure it can be perceived as cold but /…/ there is a part /…/ which is kept at normal room temperature. And then they have protective clothing /…/ but then it is up to the people working there if they put on their jackets. (Building manager)

When the suggestion to lower the winter temperature to eight degrees is discussed, they stress the importance of informing the staff who work in the museum about the reasons behind a change in the thermostat setting. In their opinion, it is necessary that there is common agreement about such a change, especially since the thermostats are individually controlled: "…so that no one enters a room and feels that, oh, how cold, here we have to turn up, turn on some heat".

The issue of thermal comfort is, by the time of the interviews, dominated by a latent conflict caused by a suggestion to lower the winter temperature. The guides and housekeepers have thermal comfort at the top of their personal agendas, but they are aware of the fact that thermal comfort is seen as a necessary evil by other more powerful actors. They also feel neglected and excluded from decision making, an exclusion that probably entrenches their negative position. From the building manager's and the conservator's points of view, the negative consequences from opening this Pandora's Box outweigh potential benefits. We see here how the "anticipation of the intention of Others" [24] polarizes positions and contribute to a state of indecision and uncertainty.

5.3. Energy – subordinate degree of priority

Energy use is considered subordinate to the other rationales for the extent of indoor climate control. Even though the cost and environmental impact of energy use are part of an ongoing discussion, they are not considered important enough to actually have an impact on the various positions.

For instance, the building manager who has the financial responsibility for the building, including the cost for energy, does not consider the fact that the heating uses a lot of electricity to be a major problem. Even though he would like to decrease the use of energy, he can only do that if there is no risk to the building fabric, and if the organizations who are responsible for the movable objects agree. Furthermore, at present there are other buildings in his stock where they can more easily carry out efficiency measures and lower the total energy use.

The other building manager, who has more the role of an architect, argues in favour of electric radiators. There is also a suggestion to install these in a previously unheated part of the building:

> It could be considered strange that electric heaters are proposed; they are maybe the least energy efficient, but with regard to installation work and the consequences it brings it is still the measure that we have prioritized. We have thought that the benefits outweigh the possible energy loss. (Building manager)

One of the conservators answers the question if they have any policies on energy efficiency in their organization as follows:

> Yes, we think energy efficiency is good! Joking apart, a lot of the things we want are things that actually use energy, we want heating and dehumidifiers and such. (Conservator)

With this ironic reflection, he points at the difficulties of incorporating a reduction of energy use in his practical work. Apparently, the limit for what is considered to be an acceptable indoor climate with respect to preservation has been pushed in a direction where energy using machinery is often inevitable.

Taken together, it is clear that the need to reduce energy is considered subordinate to other needs. Instead, it becomes manifest as a general, looming and uncertain pressure with impact more on the conscience of individuals than on their actions.

6. Discussion

It is easy to take it for granted, that organizations and individuals with responsibility for historic buildings will more or less automatically make decisions to accommodate their indoor climate control system to recommended thresholds for temperature and humidity. This case study is an example of the difference between this ideal image of decision making and the much more messy and opaque process found in practice [13].

When studying the varying practices and sequences of events at the historic house museum, it has been remarkable to note how small effect strategic decisions have actually had on the climate control system and the overall control regime over a period of close to a hundred years. Interestingly enough, this situation of stability remains today despite the fact that individuals from all the professional groups have strong opinions about the indoor climate, and despite the fact that considerable interests are at stake.

Throughout the years, there have been few noticeable changes. Still, a continuum of minor adjustments is carried out on a daily basis, often as direct responses to external stimuli; condensed water is discovered on the textiles in a bed and it is decided that the room should be fitted with an extra radiator, a window is leaking and has to be made watertight, thermostats no longer function correctly and have to be replaced. These actions, however, are adhoc; they are not the result of strategic decision making. Frequently it is the unexpected that impel action: the vacuuming of the radiators which inhibits the drying effect in autumn; changed fire protection measures in the form of closed doors between heated and unheated rooms which lead to moisture problems; a prohibited change of temperature settings results in a need of shielded thermostats, and so on.

Someone still may argue that the fact that the indoor climate control system has been kept more or less intact for so many decades certainly must be a result of conscious decisions. The evasive answers on the direct question of the rationale for the current heating practice do not support this, however. It seems more plausible to explain the current practice as a product of an historical unfolding of events than as the outcome of rational aspirations. Most of these events seem to be of coincidental nature, for example that the building was chosen for a state-supported intervention in the 1920´s (motivated by a surplus of power during night-time from the new national power grid), or that the replacement of thermostats lead to negative experiences.

Thus, taken together, we have not seen much which supports the 'traditional perspective' on strategic decision making [11], touched upon in the introduction. One way of giving a more realistic picture of the processes we have seen here, is to apply Langley *et al's* concept 'issue streams' [25] on the discussions and perceptions on preservation, comfort and energy. Their description of these processes as "continuing and interacting streams of issues that spin off actions, sometimes through identifiable decisions" [25] is more in line with our results, and clarifies how negotiations about the indoor climate are part of a more complex process, partly dependent on earlier decisions, controversies and actions. First of all, it is important to note that the indoor climate has to fulfil several purposes which are not always readily compatible. Naturally, the temperature and humidity should be adapted to the building in order to preserve it, but also to make it possible to open up for visiting tourists. The same applies to the varying kinds of artefacts within the museum; the textiles, art collections, furniture etc. All of these should be preserved for future generations, but also be exhibited to the general public. Furthermore, the indoor climate should provide plausible working conditions for the guides and housekeepers who work in the museum on a daily basis and, preferably, the climate control technology should meet these multiple demands in an energy efficient way. As a consequence, responsibilities for the building, and the artefacts and human beings within it, are spread out among a number of organizations. Each of these is represented by individuals with specific professional backgrounds, and with specific responsibilities and priorities with respect to the purposes above.

Thomas [26] and Henning [20] have argued that one reason why certain conflicts will not easily be resolved through mutual understanding is that different worlds are occupying, or at least overlapping, the same physical space. This statement seems most applicable to the situation at the studied house museum, where the different social actors relate to the same space in entirely different ways. We have seen for example, that for those who work at the museum on a daily basis, the question of appropriate indoor temperature fill up a large part of their time; as a subject for conversation, as a worrying daily embodied experience, and as a number of practical tasks to handle. Latent conflicts are now and then threatening to surface due to incompatibilities between the requirements of this staff and the management objective to preserve the building.

Even so, guides and housekeepers do not seriously contest the managers' and conservators' interpretation of how preservation may best be achieved. Despite the fact that there are damages caused by the indoor climate today, there is a shared understanding that the current situation is within the confines of an acceptable risk level. Thus, on an overarching level, there is consensus and acceptance of the fact that preservation must be the dominant rationale for indoor climate control, and all actors seem to argue for the keeping of status quo, albeit in different ways. This varying degree of priority among the three main rationales for climate control could be described as a hierarchy, with 'preservation' at the top, 'energy' at the bottom, and 'comfort' somewhere in between. The two last are clearly subordinate to the preservation task, and all interviewees seem to share this basic horizon of perception, framing their expectations for what is considered possible to achieve and decide upon [13].

The situation is partly in line with the previously mentioned article by Walker, Shove and Brown [23]. Their article shows how a certain kind of motives, 'clinical priorities', had become an institutionalised rationale for why air conditioning should readily be accepted in an increasing amount of situations. In our case, the aim of preserving the building and collections has a similar hegemonic position. However, the effect is almost the opposite: rather than pushing the growth of new indoor climate technologies, as in the North UK hospital case, we see here how "acceptable" conditions with respect to the hegemonic motive of preservation actually hamper a change of practice, leading to only rare and minor adjustments of the existing technology for climate control.

Through a technical lens, the advantages and energy-saving potential of using more sophisticated temperature control to stabilize relative humidity may seem obvious. However, from an inside perspective, such alterations are less self-evident. Both conservators and managers are well aware of the risks involved in each adjustment of the indoor climate. To preserve heritage buildings and cultural collections with mixed materials is a delicate matter, and some of the conservators and managers have had bad experience of previous attempts to intervene. Therefore, any attempt to reduce energy consumption presents a new threat to the achieved balance of temperature and humidity. Another perceived risk to the building and its preservation lies in the suppressed conflict with the permanent staff, who opposes further decreases in temperature. Guides and house-keepers are both formally and informally excluded from discussions about preservation, which are reserved for professionals such as architects, managers and conservators. However, when the lowered temperature setting was to be realized they still had the final saying, by protesting about worsened working conditions.

This case study has illustrated how discussions among and between social actors, as well as the way their respective priorities are negotiated, are essential features of the actual management procedure and have a strong impact on the ability to modify it. In this case, several interrelated aspects tend to reinforce the stability of current practice. Maybe most important is the fact that the different professionals have difficulties in reaching consensual compromises in ways which do not conflict with, or threat, the overarching objective; to preserve the building and its content. One effect of this is that neither energy saving, nor thermal comfort, are discussed in more explicit or formalised ways.

Although it could be argued that there are more optimal technical solutions available in this case, it is also clear that the present solution has proven to be a durable one, and hence, sustainable from the viewpoints of the involved organizations. From a systems perspective, there is a risk in leaving a state of stability, as there might be unknown risks connected with the transition [27]. Furthermore, to solve problems by increasing the complexity of the system might have adverse effects in the long run [28].

Moezzi and Janda [19] suggest that research exploring technical or behavioural potentials for energy-efficiency tends to generate too simple solutions, while the use of "social potentials" increases the complexity of solution sets. Our findings support this by exposing how social aspects are paramount for enabling change. Still, we suggest that the viable way to improve the indoor climate in heritage buildings, and to do so in an energy-efficient way, is to support decision making that pay attention to the case-specific perspectives and interests of the involved actors.

7. Conclusion

The objective of this paper is to show how the interaction between perceptions and experiences of different professional groups are pivotal factors for the management of the indoor climate in heritage buildings. As described in the introduction, the academic discourse about indoor climate control takes for granted the idea that action is subsequent to a situation of choice and that the fundamental role for research is to produce expert knowledge which can guide decision-makers in such situations. The main conclusion from this study is that this idea has substantial limitations. In this case study the present practice has emerged and stabilized in the absence of a rational decision process comprising the identification and evaluation of alternatives. Instead of decision process per se, there is a discourse about indoor climate control that forms separate, but linked, "issue streams" where each actor take a unique position based on experience and pre-understanding.

If the indoor climate control in the museum had been analysed from a technical viewpoint, it is likely that an observer from outside had identified several interventions, either to improve the indoor climate or make its control more energy efficient. It is also likely that this observer would be puzzled about why such interventions had not yet been realized, and discussed this in terms of a "gap" which ultimately could be attributed to the irrational behaviour of individuals. We have taken another route and approached the organizational setting from within, by focusing on each actor's perceptions and experiences. In the light of our findings, the very existence of the "gap" could be contested and the arguments given by different actors turn out as rational. This is imperative from a policy perspective: if there is an ambition to change practices towards more sustainable trajectories, then there is a need to transcend mere technical approaches and include social factors.

We therefore propose, for this field, an increased use of research which focus on the interaction between relevant social actors (and their varying habits, experiences and modes of thinking) and the social and material prerequisites for their respective ability to act. This would provide a much more informed basis for further actions in museums and heritage buildings concerning the delicate balance between preservation, thermal comfort, and energy efficiency.

Despite being an isolated, single case study in the Swedish context, we further suggest that the findings from this case study have international relevancy. The management of historic buildings is organized in different ways across countries, but the challenge to combine low energy use with preservation is universal. The management of built and movable heritage has become a highly professionalized enterprise [29] with an increasingly globalized community of practitioners. Among heritage professionals there is a nascent understanding of sustainability as a key issue and aim for conservation practice e.g. [30]. There is however a tendency that sustainability as a theme is used to legitimize the actions of heritage professionals via a change in discourse, without profound changes of actual practice [29]. The case study in this paper reveals the complexities surrounding such a change and opens up for a re-framing of how a more sustainable management of historic buildings can be achieved.

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Paper V.

Making sense of climate risk information: the case of future indoor climate risks in Swedish churches

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Abstract

Organizations and institutions managing built heritage have to make use of increasingly detailed, elaborate and complex climate change impact assessments. It is a challenge to determine how, when and by whom climate predictions should be translated into risk estimates usable for decision-making. In this paper results from the Climate for Culture project are used to study how heritage decision-makers interpret future indoor climate-related risks to Swedish churches. Different sets of risk maps were presented to ten engineers, ten building conservators and five experts on indoor climate related risks. Interviews were used to understand how the interviewees made sense of the presented information and if they associated it with a perceived need for adaptation. The results show that the risks were interpreted and assessed largely dependent on their pre-understanding and familiarity with the individual risks. The magnitude of change and the lack of uncertainty estimates were subordinate to the overall impression of the information as being credible and salient. The major conclusion is that the dissemination of risk information, also from projects which at the outset have aimed at producing knowledge relevant for end-users, should be both customized and tested in collaborative efforts by stakeholders and scientists.

Keywords

Risk communication; Cultural heritage management; Sensemaking; Adaptation

1. Introduction

In recent years there has been much effort invested to assess the impact of climate change to cultural collections and built heritage in Europe. The predominant approach has been to use top-down modeling where the outcome is predictions of how deterioration rates and patterns will change in the future. This is a necessary but not sufficient condition for the planning and implementation of adaptation and mitigation measures. In order for the risk assessments to have an effect they must be communicated to the end users. The overall problem addressed in this paper is how generic, complex and uncertain risk information should be disseminated to adaptation practitioners in the heritage sector.

The impacts of climate change on built heritage have been studied both for individual sites e.g. (Grossi *et al.*, 2011) and for geographic areas e.g. (Sabbioni *et al.*, 2010). The NOAH's ARK project (Sabbioni *et al.*, 2010) assessed the effects of climate change to cultural heritage in Europe by applying damage functions to projections of the future climate. The main result of the project was a collection of maps over Europe, where key environmental variables were linked to potential damage for heritage materials. Recently, there have also been studies on how the indoor climate in selected historic buildings and the related risks will be affected by climate change (Bratasz *et al.*, 2012; Brimblecombe and Lankester, 2012; Lankester and Brimblecombe, 2012b, 2012a). Huijbregts et al (2012) showed how simplified building simulation of generic buildings is a feasible methodology to produce maps of future indoor climates. The methodology was applied at a large scale in the recently finished project Climate for Culture (Leissner *et al.*, 2014), which aimed to produce information useful for the management of historic buildings and cultural collections in Europe.

Organizations and institutions responsible for cultural heritage management now face the challenge of how to make use of increasingly detailed, elaborate and complex impact assessments in decision-making for climate change adaptation. It has been suggested that predictions of earth-system processes are most useful for decision making when they are related to near-term events and when predictive skill is known (Sarewitz *et al.*, 2000). Predictions of climate change impacts are both highly uncertain and relate to events which, in a heritage management perspective at least, are located in the distant future. Despite this there is a demand from policy-makers and adaptation practitioners for more detailed and refined predictions about climate change impacts to cultural heritage, and a scientific community keen to supply this demand. However, to what extent existing predictions of impacts to cultural heritage have been useful for adaptation planning remains largely unknown. This situation calls for an urgent need to understand how researchers and stakeholders can collaborate to transform abstract and complex information about uncertain climate change impacts into actionable knowledge for adaptation decision-makers in the heritage sector.

The point of departure for this paper is the intersection between results from Climate for Culture (CfC), a research project supplying risk information, and the Church of Sweden, an organization in need of risk information for adaptation planning. In this intersection, concerns were raised about how the risk information should be selected, packaged, and assessed, and to what extent it actually was rendered as useful by decision-makers. To better understand the process of how the quantitative results of this and other climate change impact projects should be communicated, this exploratory study uses qualitative interviews to get a better understanding of how complex and uncertain risk information is subjectively interpreted by decision-makers.

The CfC project used climate modelling and building simulations to produce a set of European maps depicting future changes of deterioration for materials kept inside historic buildings. The project set out to produce results relevant for end-users by involving stakeholders throughout the research process. Dissemination of results was inscribed as a critical factor for reaching the project's aims. Questions about the identities of the end-users and the ways in which the results could be used received some attention in the initial phase of the project. A quite heterogeneous user group could be anticipated, ranging from policy makers at the national level to private owners of historic buildings. It was decided that the main strategy for dissemination should be to make results of the project easily accessible for decision-makers to choose based on their own needs (Leissner *et al.*, 2014). There had been a process internal to the project where technical experts collaborated with stakeholders in the design of the maps. This kind of procedure is known to be insufficient to guarantee effective communication (Morgan *et al.*, 2001, p. 19).

The Church of Sweden is responsible for the majority of historic churches in Sweden. During 2014, the organization investigated potential ways of re-organizing their building management. An assessment of climate change impacts to churches was considered necessary in order to understand the future need of adaptation. The results of the recently finished CfC project became a timely opportunity for delivering the kind of information sought by the Church of Sweden.

In the researcher-stakeholder dialogue that followed, a key question was identified: how the quantitative information produced by CfC should be transformed into statements about risk usable for adaptation planning. The results from CfC are meant to be used by heritage professionals whom have the necessary knowledge about local circumstances to judge the relevancy of the information in relation to specific cases. Building management expertise from within the Church of Sweden had to be involved in the risk assessment process to contribute with the necessary local knowledge – but it was uncertain how this should be carried out. Therefore, it remained a challenge to determine how, when and by whom the predictions made by CfC should be translated into risk estimates usable for the decision-making process.

How scientific information successfully translates into action has been described as a key question for climate risk management (Travis and Bates, 2014, p. 1). Empirical research has shown how the use of information in decision making can be dependent of a range of factors, such as institutional barriers, resolution of the information, level of skill among users, trust between producers and users, etc. (Kirchhoff *et al.*, 2013). It has been suggested that to create actionable knowledge, information about climate change must fit into existing contexts to close the usability gap between what scientists understand as useful information and what users recognize as usable in their decision-making (Lemos *et al.*, 2012). To achieve this, there is a need to tailor climate information through sustained interactions between researchers and decision-makers (Lemos *et al.*, 2012, p. 789; Moss *et al.*, 2013, p. 697). Previous studies addressing the usefulness of climate risk information for heritage practitioners have pointed out the necessity to contextualize climate change information in order to make it relevant for practical management (Cassar and Pender, 2005; Haugen and Mattsson, 2011).

There is no shortage of advice for how to communicate risk and uncertainty effectively e.g. (Morgan *et al.*, 2001, p. 19; Renn, 2008; CCSP, 2009; Fischhoff, 2011; Mastrandrea *et al.*, 2011; Fischhoff and Davis, 2014). One thing that different strategies have in common is that risk communication should focus on issues that are relevant for the target audience. Another commonality is the importance of testing communications before final dissemination. Despite the abundance of advice, there is little empirical evidence on the efficacy of different strategies for climate communication (Pidgeon and Fischhoff, 2011). Furthermore, there are competing understandings of what constitutes good risk communication and different ends will require different sets of best practices (Demeritt and Nobert, 2014).

It has often been argued that uncertainties in climate change impacts should be characterized, quantified (based on historic data or expert judgment) and communicated to the end user in order to improve decision-making e.g. (Mastrandrea *et al.*, 2011), although the procedures, scope and purpose of this enterprise is debated (Adler and Hirsch Hadorn, 2014). Most impact studies on indoor climate risks to buildings have been of a deterministic nature, despite calls for probabilistic approaches where at least some of the uncertainties are quantified (Wilde and Tian, 2011). Uncertainties in one modelling step will propagate to the subsequent step. As an example, Nik (2012) shows how uncertainties in global climate models have substantial impact on building simulations. The prediction of future indoor climate-induced damage in buildings introduces an additional layer of uncertainty (Leijonhufvud *et al.*, 2013). The functions used for modelling damage to cultural heritage are rarely probabilistic (Strlič *et al.*, 2013). As an example, a recent review concluded that all mould growth models are deterministic (Vereecken and Roels, 2012). There remains the possibility to address other (known) uncertainties. Of interest for this paper is a study by Nik et al (2012), which takes into account the uncertainty of future emissions when predicting future mould growth in ventilated attics in Sweden. The study by Lankester and Brimblecombe (Lankester and Brimblecombe, 2012b) on the impact on future climates on historic interiors also compared different emission scenarios.

While addressing known uncertainties is considered good practice, it will always increase the amount of modelling and analysis needed. In the already complex CfC-project it was considered unfeasible to introduce more modelling parameters. Consequently, the CfC-project produced single point estimates of future damage (with the exception that two actually quite similar forcing scenarios were used). In practice, the results can be said to be based on a "series of best guesses", which means that there is no uncertainty range coupled to the final result (Schneider and Kuntz-Duriseti, 2002, p. 68). This is problematic as a decision-maker might interpret the information as representing the most likely future scenario. Furthermore, the high resolution of the result might lead to false reductionism, i.e. that a more detailed model creates an illusion of realism (Dessai *et al.*, 2009). There is also a risk that the map format in itself adds to a sense of precision and legitimacy obscuring uncertainty (Preston *et al.*, 2011).

The deterministic approach used by CfC does not preclude the results from being usable for decision-making – but who should do the necessary transformations from point estimates to risk assessments, and under which circumstances? On the one hand it has been suggested to let those with most knowledge make subjective estimates of risk instead of passing uncertainty on to lay-people (Schneider and Kuntz-Duriseti, 2002). On the other hand scientists should refrain from summarizing complex and uncertain information on behalf of policy makers (Stirling, 2010). The risk information produced by CfC integrates expertise from several fields (i.e. climate science, building physics, conservation) and both scientists and stakeholders have collaboratively contributed to determine the procedures for establishing the end result in the form of European maps. Consequently, the lines between producers and users, experts and lay-people are not easily drawn in this case.

Much of the literature on best practices in risk communication is based on an understanding where the overall goal of risk communication is to transmit "risk messages" without distortion to inform, and not influence, decisions (Demeritt and Nobert, 2014, p. 315). As an example, risk communication has been described as intended to help decision-makers to make informed, independent judgments about risks (Morgan *et al.*, 2001). It is common that psychological factors such as cognition and emotion are used to explain how risk messages are misunderstood and biased, while the cultural and social nature of risk is downplayed (Boholm and Corvellec, 2010; Granderson, 2014). Conceptualizations of risk as a transferable message correspond to objectivist approaches to knowledge, in which knowledge is unproblematically separable from the scientist who produced it and the practitioner who may use it and where communication is essentially one-way and linear (Greenhalgh and Wieringa, 2011).

The risk message model fits into more

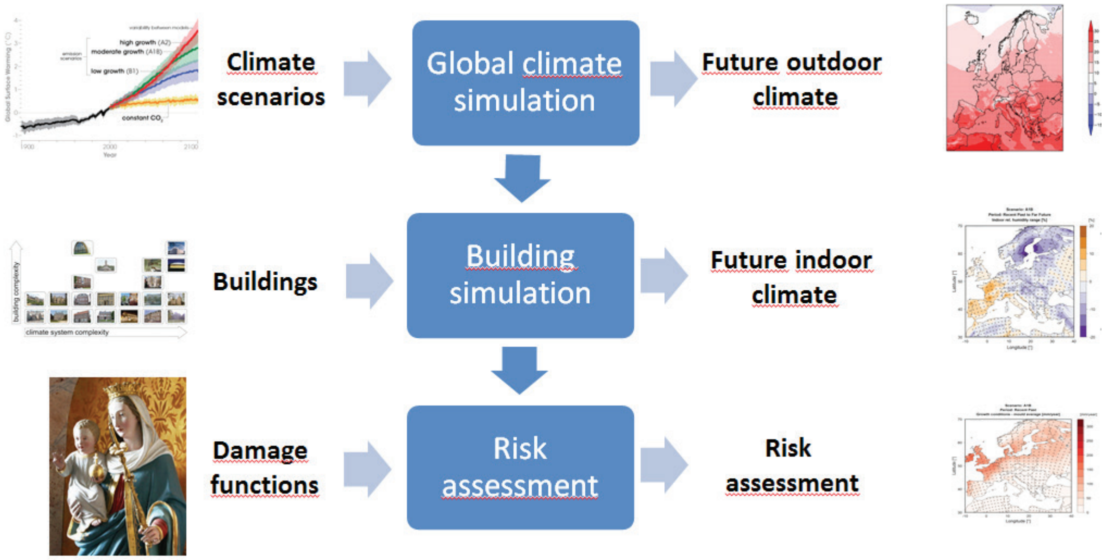


Fig 1: The method to produce risk maps developed in the Climate for Culture-project (Leissner et al., 2014).

overarching ideas of governance as a matter of "predict-then-act" (Adler and Hirsch Hadorn, 2014). However, practical risk governance tends to deviate from the prescriptions and ideas conveyed in formal risk management protocols (Boholm *et al.*, 2011). Boholm et al (2011) show the importance of sense-making processes when planners deal with risk, and how scientific assessment procedures advocated in risk management guidelines are substituted by social processes of negotiation.

The lack of uncertainty estimates in the CfC maps, the complexity of the modelled processes and the blurred line between producers and users make it difficult to test how well the information, understood as a risk message, is transferred to a user. It is impossible to examine to what extent the information is "biased" as there is no objective yardstick to compare with. This ambiguity inherent in the information does not imply that there is no use in trying to understand how it is interpreted and understood by users. On the contrary, it could be argued that it is even more important than if there was consensus among experts about the magnitude of the risk.

To better understand the processes involved in the communication of the risk maps there is a need for an exploratory and qualitative way of inquiry, and the Church of Sweden serves as a relevant case study for this aim. Hence, the major objective of the paper is to explore and understand how the generic, ambiguous and complex climate risk information produced in the CfC-project is interpreted by decision-makers in the Swedish church. A secondary objective is to develop a methodology for how to select adaptation-relevant parts of the risk information produced by CfC and pre-test its dissemination to a specific target audience.

2. The Climate for Culture project

The Climate for Culture project (CfC) was a five year Large Scale Integrated Project within the EU Seventh Framework Program completed in 2014. The general objectives of the project were to quantitatively assess the effects of climate change on cultural heritage in Europe and to discuss mitigation strategies in connection to this. One main outcome of the project was a method to produce risk maps for Europe. A brief introduction to the method is given below, more details can be found in Leissner et al. (2014) and Leissner et al. (2015).

The climate model REMO, developed at the Max Planck Institute of Meteorology, was used to produce regional simulations of the climate on a grid of about 11 km. Two global circulation models were applied as driving force (ECHAM5-MPI-OM and MPI-ESM) (Leissner *et al.*, 2014). The simulations were carried out for three 30-year periods: 1961-1990 (recent past), 2021-2050 (near future) and 2071-2100 (far future). The simulations for the future were forced with two different emission scenarios (A1B and RCP 4.5), while the simulations of the recent past was forced with observed greenhouse gas emissions. Past and future climate data in the form of hourly values for the whole 30-year periods were produced on a European grid with more than 900 locations. The modelled climate data sets were verified with observational data sets to check their applicability for building simulation. Systematic deviations and other issues related to the use of modelled climate data were identified.

Indoor climates in 16 different generic buildings were simulated in a subset of these locations by the use of a simplified hygrothermal building model. A state-space model was used comprising a mathematical function, derived from a statistical analysis of measurements, that calculates the indoor climate from the outdoor climate. The model has been validated by (Kramer *et al.*, 2013).

Changes in future damage were assessed based on damage functions, i.e. equations or algorithms that relates quantifiable factors in the environment to quantifiable changes within the object. The damage functions that were used by CfC include:

- Mechanical damage: wood, painted wood
- Chemical damage: paper, textiles, photographic material
- Biological damage: mould growth, insects

Finally these changes were presented as maps over Europe either showing the absolute values for the three time periods or the change in damage in relation to the recent past (see fig.2).

3. Method

The methodology used in the present paper consisted of two steps. The first step was to roughly identify the subset of the risk information produced by CfC that was relevant for adaptation planning of historic churches in Sweden. The combination of two emission scenarios, different timescales, 16 building types used for building simulation and a range of damage functions had resulted in a total of 55650 risk maps. Only a limited number of these were relevant for the Church of Sweden. The selection was done in a collaborative workshop with researchers from CfC and stakeholders from the Church of Sweden. The constitution of the stakeholder group was chosen by the Church of Sweden and comprised both top-level management and engineering and conservation professionals directly involved in management. Based on the discussions in the workshop, a set of risk maps was chosen by the researchers from CfC.

After the selection of risk maps made in the workshop, the next step was to study how adaptation decision-makers interpreted the selected maps, how the information fitted into their existing decision context and if it translated into a perceived need for adaptation. Based partly on the stakeholder experience of knowledge acquisition within the Church of Sweden, it was decided that the most efficient way to elicit information was to use telephone interviews. The interviews were semi-structured, revolving around a questionnaire that was sent to the interviewees beforehand. The questionnaire was divided in three sections. The first section described the aim of the study and gave background information about the CfC-project and the production of risk maps.

The second section contained pairs of maps, depicting climate change impacts for the generic building type representing an unheated small stone church (fig.2). The pairs consisted of one map showing the recent past, and one map showing the difference between the recent past and the near future. For each pair of maps there were three identical questions. The first question considered risk assessment. The rationale for using an ordinal scale is that such scales are commonly used in practical risk assessments, for example when doing environmental impact assessments (Boholm, 2010). The two other questions were about the need for adaptation measures and what kinds of adaptation measures that were considered relevant for the risk in question. The pairs of maps (mould growth, insects and salt damage) were chosen to represent different degrees of severity and uncertainty.

The third section consisted of questions of indoor climate control and indoor climate-related risks in churches today. They were constructed to reveal problems and opportunities with existing management processes as well as identification of both technical and non-technical barriers to improved indoor climate control in churches. There were both questions with predefined answers and open-ended questions.

The rationale for the chosen format of the interview (a combination of qualitative interview and survey) was the qualitative and exploratory character of the research question. The aim was to understand how the risk information conveyed in the survey-like questions was interpreted by decision-makers. The risk assessments are interesting on their own but the focus is here on sensemaking: the process in which the interviewees renders the information as intelligible and relate to it (Weick, 1995). The interviewees were therefore instructed to "think aloud" and explain the rationale for all answers, a method often used for pre-testing surveys (Collins, 2003). In cases where the interviewer felt that the verbal accounts didn't reveal enough information, interviewees were probed with cues such as "explain how you came up with that answer", "what are your thoughts on…?".

A category of key actors regarding adaptation planning in the Church of Sweden were identified at the workshop. At the Diocese level there are engineering and heritage professionals employed to support parishes with all aspects of the management of churches. Typically, there is one engineer and one building conservator employed by each of the thirteen Swedish Dioceses. These professionals give support to the often layman-led management of the individual churches, both regarding daily operation and renovation projects. They have good, aggregated, knowledge of risks to churches in their geographic region because of their strategic position and tight collaboration with individual parishes. However, they are not specialized in indoor climate-related problems. Interviews were made with ten engineers and ten building conservators. In the rest of the paper these are referred to as "decision-makers".

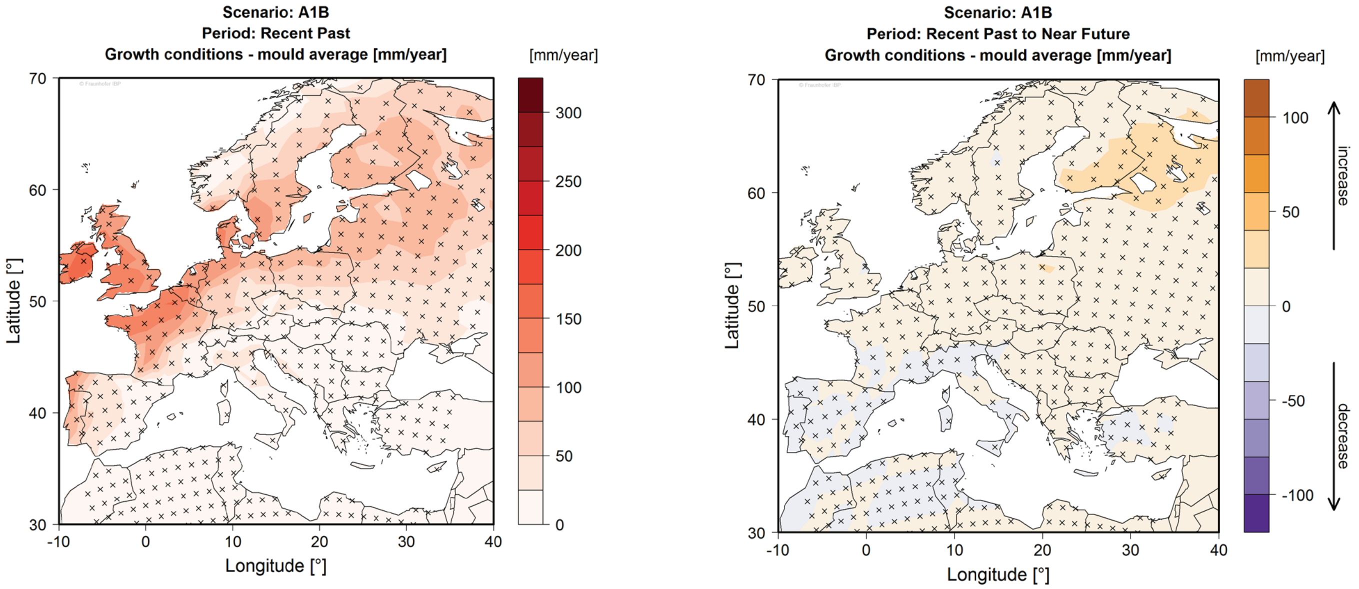
To compare the assessments made by decision-makers, five experts regarding indoor climate risks were also interviewed. Two mycologists, one entomologist and two engineers specialized in climate-related damages in buildings were interviewed regarding the pairs of maps that were within their area of expertise.

The interviews were made over telephone in August-September 2014. Each interview lasted between 30-80 minutes with an average of 45 minutes. The interviews were recorded and notes were taken. All quotes have been transcribed verbatim and translated into English by the author.

4. Results and analysis of the interviews

The following analysis begins with some general reflections on the perception and interpretation of the risk information as a whole, and continues with a more in-depth analysis regarding how two specific questions in the questionnaire were interpreted.

Most interviewees seemed to have read the material carefully and tried to answer the questions with care, despite a low degree of familiarity with the technical details. All but one of the 21 decision-makers that were contacted for the interviews were able to participate with short notice,



Mould growth. The picture to the left shows the reference period and the figure to the right the difference between the reference period and the near future. The mould growth has been calculated on the basis of temperature and relative humidity. Scale: mm/year. One example: In Gothenburg there is in the reference scenario a mould growth of 100-125 mm/year in the building. The growth is expected to increase with between 0-20 mm/year in the near future. Observe that there is expected mould growth already today in this type of building, except in the northwest of Sweden.

how do you assess the changed risk level? (negligible, small, substantial, serious, unable to assess)

should this information lead to any adaptation measure? (yes, no, unable to assess)

what kind of measure would that be?

Figure 2. Excerpt from the questionnaire. Question on mould growth (translated from Swedish).

which indicates that they had an interest in the subject matter. There was consensus among decision-makers and experts that the presented risk information was relevant. They could all relate to the content and found it interesting. Despite perceiving the information as relevant, two of the experts did not perceive the information as reliable enough to be of any use.

Most of the interviewees expressed that it was relatively easy to understand what the risk maps showed. However, as discussed in more detail below, the way they referred to the maps indicated that their technical comprehension sometimes was flawed. Most interviewees were hesitant to make any kind of risk assessment, as they perceived the information to be too abstract, unspecific and uncertain. However, in the end only a minority chose to use the “unable to assess” option. One building conservator expresses her concerns about assessing the maps in this way:

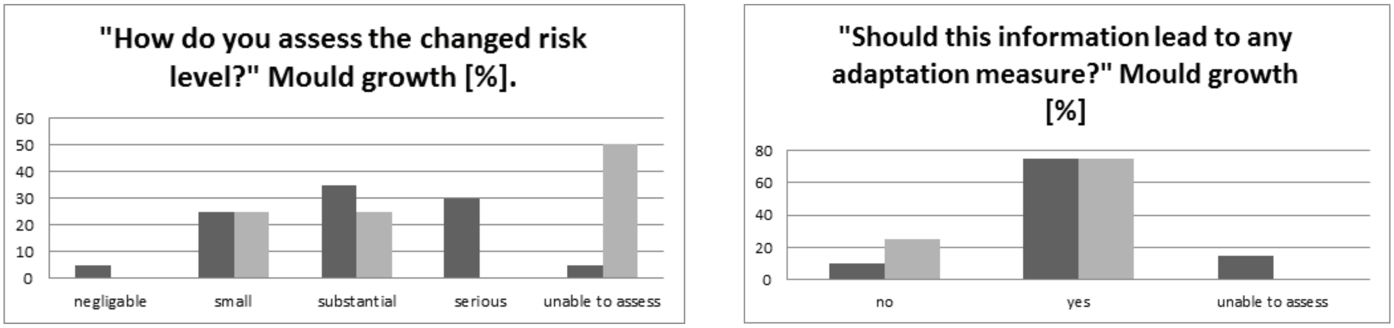


Fig 3a and 3b. Mould growth. Decision-makers (n=20) in dark grey, experts (n=4) in light grey.

> It is difficult to interpret, expert knowledge is needed… difficult to relate to the numbers. I understand that all this is dependent on a lot of hypothesizing at the drawing table… there is a need of a pre-interpretation.

The main objectives of the interviews were to understand how the interviewees interpreted the different pairs of maps, how they assessed the risks and if they related the information to a need for adaptation measures. The questions regarding mould growth (fig. 2) and salt damage (fig. 4), will be used here as examples. These questions were chosen because of their differences regarding the familiarity of the type of damage and the strength of the climate change signal. Mould growth is a common problem in Swedish churches, with a cause-effect relationship assumed to be well known to decision-makers. Salt damage, on the other hand, is not as common, and the understanding among decision-makers of the cause-effect relationship was assumed to be lower. Furthermore, while the predicted climate change impact on mould growth is significant, the impact on salt damage is negligible.

The quantitative distribution of answers is to illustrate the variety of responses. An analysis of how individuals explained their reasoning behind their answers, in some instances after being cued to do so, is used to interpret the quantitative results.

The mould growth maps (fig 2) show predicted mould growth for the A1B emission scenario for the recent past (left) and the change between recent past and near future (right). Mould germination and mycelium growth were calculated on hourly values for the 30-year periods, using RH and T isolines from Sedlbauer (2002). The maps show the average growth per year for the whole 30-year period. For the recent past, the map shows a predicted mould growth between 0-125 mm over Sweden, with the lowest values in the northwest, and highest in the southwest. The change map shows an increase with 0-20 mm over the whole country, implying a possible maximum relative increase in the southwest of about 20 %. However, the change can also be zero as the value can be anywhere in the range between 0-20 mm.

The risk assessments for this pair of maps varied considerably (fig 3a). Only one of the decision-makers assessed the risk as negligible, while the other answers were about evenly distributed between small, substantial and serious risk. One decision-maker was unable to assess the risk. The assessments from the experts , in this case two mycologists and two engineers working with moisture problems in historic buildings, were quite varying in that the mycologists considered themselves unable to assess the risks, and the engineers assessed the risk as small and substantial, respectively. The question if the information on mould growth should lead to an adaptation measure was answered affirmatively by 75 % of both decision-makers and experts (fig 3b).

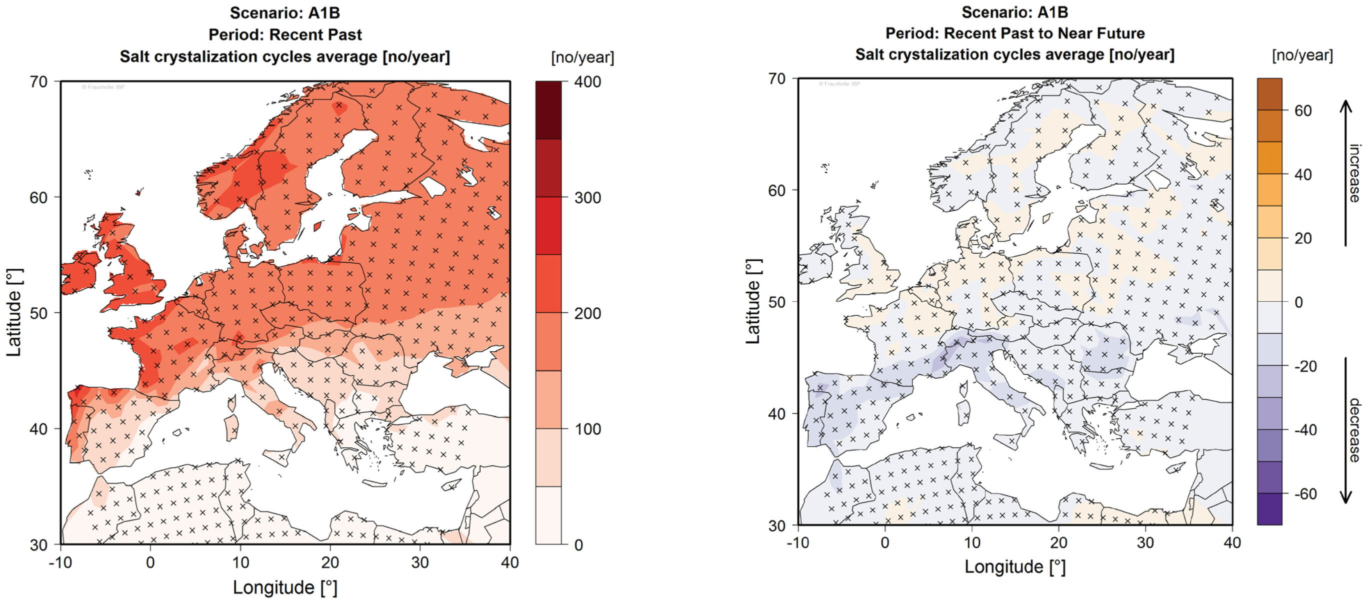
The results show that the level of assessed risk for the mould growth maps varied both within and between the groups of decision-makers and experts. In the following, a number of individual accounts are used to illustrate how the same information is interpreted in different ways within the groups.

The reasoning of one of the decision-makers shows how the combination of a perceived weak signal, high uncertainty and a skeptical attitude toward the method results in an outlier assessment. This decision-maker assessed the increased risk level for mould growth as small and answered the question of the need for adaptation measures negatively. He reportedly had a long experience with mould problems in churches. On the basis of his experiences, he suggests that the link between mould problems and climate change is weak compared to the influence of other factors:

> …we see changes [of the extent of mould growth] already today but it is nothing that worries me, there are much bigger problems concerning other aspects [that affects the risk for mould problems in churches].

He expressed an overall skepticism regarding the possibility to at all doing these kinds of predictions, claiming them to be “too general” and “too uncertain”. At the same time, he seemed to be able to interpret the maps in a technically correct way and paid attention to technical details. In sum, this individual seemed to perceive the information as lacking in saliency (the change being too small) and credibility (too much uncertainty), and therefore did not consider it as usable.

In contrast to the technical and rather critical approach represented by the former example, there were several decision-makers whose risk assessments seemed to be biased by a preconceived impression of a negative development. Hence, the details of the information regarding the specific question were downplayed in relation to



Salt damage: Number of occurrences when the relative humidity passes 75 % (NaCl crystallizes). The picture to the left shows the reference period and the figure to the right the difference between the reference period and the near future. An example: In Gothenburg the 75 % relative humidity threshold will be passed 150-200 times per year. In the near future this number is expected to increase with 0-10 times per year.

how do you assess the changed risk level? (negligible, small, substantial, serious, unable to assess)

should this information lead to any adaptation measure? (yes, no, unable to assess)

what kind of measure would that be?

Figure 4. Excerpt from the questionnaire. Question on salt damage (translated from Swedish)

the overall impression. An example was one decision-maker, also with long experience of mould problems in churches, who assessed the mould risk as serious and answered affirmatively on the need for adaptation measures. This engineer seemed to make his assessment without paying attention to the actual details of the maps. Rather, he reasoned that mould problems already today was a significant problem, and that any change in the direction to a warmer and more humid climate would be a serious problem. In a way, then, the conveyed information strengthened his already internalized impression of the negative impacts of climate change. He explained his reasoning by referencing to general phenomena only loosely coupled to the presented information. In his case, the risk information was perceived as both salient and credible.

The assessments of the experts were quite diverging. One of them, a mycologist, was skeptical to the usefulness of the information, claiming the underlying science to be too uncertain. Consequently, he had a negative stance towards the

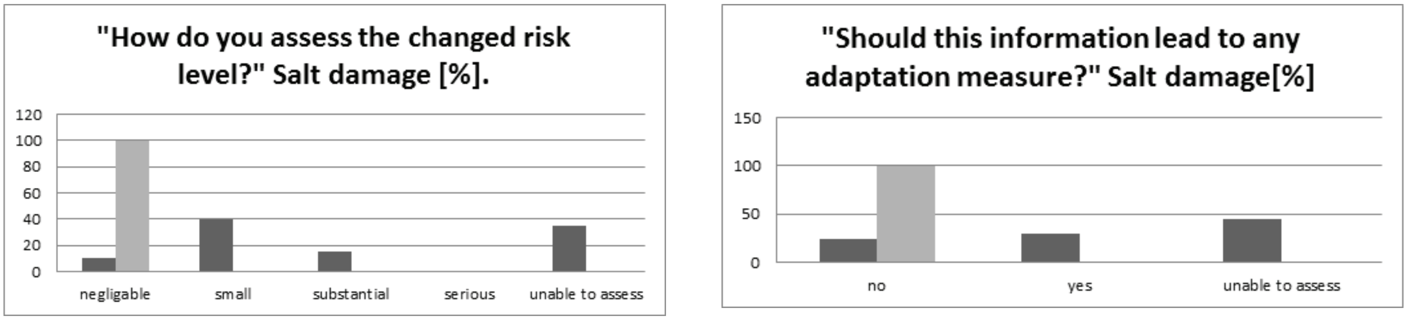


Fig 5a and 5b. Salt damage. Decision-makers (n=20) in dark grey, experts (n=2) in light grey.

methodological approach taken by CfC, grounded in skepticism towards the possibility to predict mould growth in buildings as a function of the outdoor climate:

> I consider the uncertainties too large for making an assessment of the risk possible. Furthermore, I do not think that small differences in the outdoor climate have an impact as the differences which are specific for each building are much more critical [for mould growth].

This verdict did not seem to be due to skepticism about climate change in general, but rather due to a lack of faith in the overall research approach. Hence, he did not perceive the information as credible and refrained from making any assessments based on the information.

This can be contrasted to the views of another expert, an engineer specialized in indoor climate-related risks in churches. This expert was more positive of the usability of the results and assessed the predicted increase in mould growth as substantial. As a reference point for his assessment, he explained that many churches in the southern parts of the country were close to a threshold for developing mould problems, and that even a small change could have major consequences. Interestingly, he commented on his own assessment that it was biased by his experience of an increase in mould problems in churches during the last 5-10 years, according to him likely due to a changed outdoor climate. His thoughts about this illustrate how all risk assessments are based on personal experience:

> Expert: The way in which I make my assessment is affected by my personal experience. If I didn't know anything [about problems today] I wouldn't be worried over these numbers. Actually, the best would be to find someone without preconceived notions.
>
> Interviewer: It is difficult to find an expert on mould growth in buildings lacking experience with mould problems.
>
> Expert: Yes, it is a dilemma

The salt damage maps (fig 4) show the predicted number of NaCl salt transitions for the A1B emission scenario for the recent past (left) and the change between recent past and near future (right). The number of transitions over 75 % RH (the equilibrium RH for NaCl) were calculat-

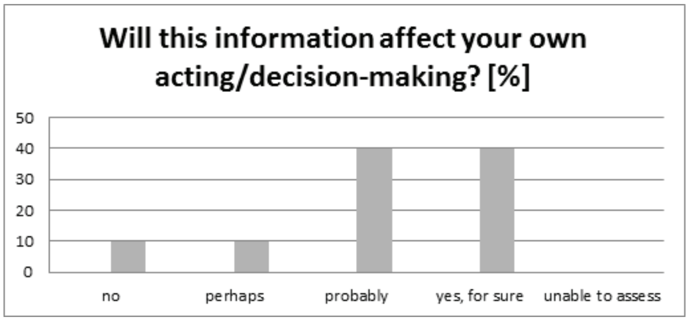


Fig 6. Answers from decision-makers (n=20) to the question "Do you estimate that the aggregated information about risks for mould/ insects/ salt damage will affect your own acting/ decision-making?".

ed on the hourly values and averaged for the whole 30-year period. For the recent past, the map shows a predicted number of 150-200 transitions per year for most of Sweden. The change map shows an increase of 0-10 transitions in the south and northeast, and a decrease of 0-10 transitions in the rest of the country. These changes are very small in relation to the overall uncertainty of the simulations.

The salt damage maps are different from the mould growth maps in the respect that it is difficult to determine if salt damage will decrease or increase in the near future. Despite this difficulty, 55 % of the decision-makers made the assessment that the information implied a small or substantial level of risk. On the question if the information on salt damage should lead to any adaptation measure, 25 % of decision-makers answered no, 30 % yes and 45 % unable to assess.

How can it be explained that a map which objectively shows a negligible impact of climate change is assessed as depicting a substantial risk? One of the decision-makers gives a hint: he argues that it is difficult to estimate a risk as the indicated change is very small, but as the uncertainty is high he still think the risk is substantial. Another reason might be that several interviewees had difficulties in understanding the difference between the baseline map and the change map. The information shown in the reference scenario seems to be used as the dominating basis for the risk assessment and little attention was paid to the expected change. Related to this, it was clear that several interviewees based their risk assessments on how problems were experienced today, ignoring the information in the maps. One decision-maker argued in this way when explaining the difficulty in using the information for risk assessments:

> all questions are intertwined /…/ it is like this that you have to base your interpretation on the situation today, when there is such a wide scope for interpretation.

Both experts assessed the changed risk level as negligible, referring to the small change as well as the uncertainty inherent in the damage function.

Fig 6 shows that most of the decision-makers thought that the presented information was likely to affect their own acting/ decision-making. The overall impression was that the information was perceived as strengthening the need for already existing ways of adapting to climate change:

> We already have these problems, but this shows

> that it is likely going to become even worse. This gives us a stronger argument for continuing with what we already do [to reduce indoor climate-related risks] . (decision-maker)

The notions of risk that emerged in the interviews diverged from the common technical definition of risk as a product of likelihood and expected outcome. The way the interviewees reasoned revealed how the term risk was used in different ways by different individuals and how ideas of risk, consequence, probability, uncertainty and vulnerability were intermingled. Risk was for example referred to as dominated by expected outcome: “the risk might become serious in rare cases” (decision-maker), or the other way around, emphasizing likelihood: “big consequences but small risk” (decision-maker).

A confounding factor for making risk assessments was the difference in the potential for risk reduction for different kinds of risk. This can be exemplified with that mould growth potentially can lead to big damages, but it is relatively inexpensive and simple to reduce the risk with preventive measures, e.g. dehumidification. Then, in a case where effective risk reduction measures are already in place, it is intelligible to assess the risk as low.

Finally, and related to the definition of risk, there were few decision-makers who seemed concerned about the absence of probability estimates or uncertainty intervals. Actually, the label “risk maps” used by CfC is misleading as they are deterministic accounts of future damage, albeit with a presumably large amount of uncertainty. However, this did not seem to bother decision-makers. There were only a few of them who discussed or questioned the uncertainty of the information. The opposite was true of the experts, for whom uncertainty and the accuracy of predictions seemed to be the dominating issue.

5. Discussion

The methodology used in this paper provided a manageable way of understanding if risk information at all makes sense to decision-makers and if it is perceived as usable in their decision-context. In contrast to a survey, it was possible to get in-depth understanding on how the interviewees interpreted complex information and how they argued for giving their answers. The results can be used for customizing risk communication in a subsequent step. Furthermore, the methodology provided a cost-effective way of eliciting knowledge on the organizational constraints and possibilities for adaptation (this aspect is however out of the scope of this paper).

The interviews showed that the decision-makers and experts in general were interested in the risk information. For most of them, the information made sense in such a way that they could relate it to their own decision context. There was also in general a high level of trust vis-à-vis the provider of the risk information. These two factors – that the information related to topical issues and the trust given to the information provider - could explain why a majority of interviewees expressed that the information would have an impact on their own future behavior.

The magnitude of the predicted change and the accuracy of predictions were subordinate to the overall impression of the information as being credible and salient, factors which previous research has shown to be crucial for increasing usability (Cash *et al.*, 2003; Kirchhoff *et al.*, 2013).

Previous research in risk communication points out the need to evaluate how risk information is perceived in order to customize the presentation of risks and to guide future research (Renn, 2008). The risk maps were in this case ambiguous to the studied group, resulting in a broad range of interpretations. For example, in the case of the mould growth maps, the assessed risk levels were ranging from negligible to serious. Both decision-makers and experts were, however, generally hesitant about making risk assessments, claiming the information to be abstract, complex and ambiguous. In the end, a majority chose to give an assessment rather than selecting the "unable to assess" option. This indicates that the risk maps gave rather weak cues in comparison to already established individual beliefs about the issue at stake, for example their opinions concerning the impact of climate change in general (Morgan *et al.*, 2001) .

A complicating factor when interpreting the interviews was the elusive nature of risk itself. There are many different types of risks as well as conceptions of how they are constituted (Renn, 2008; Blennow *et al.*, 2014). Experts and lay-people tend to use the concept in different ways, with experts preferring a technical definition where risk is characterized as a product of probability and negative consequences (Slovic, 2000). From the verbal reports of the interviews it was apparent that the understandings of risk varied considerably between individuals, and in general they did not adhere at all to the technical definition. In addition, when interviewees were asked to rationalize their risk assessments, they referred to existing or possible risk management actions, such as the extent of indoor climate control. These results points at the lack of realism in a position which states that the ideal of risk communication is the unbiased transfer of a "risk message", as discussed in the introduction. They also support previous research that shows how actors involved in practical risk governance tend to merge risk analysis, risk management and risk communication (Boholm *et al.*, 2011).

An intricate problem with the risk information used in this study is that it shows possible future harm without giving any information about the likelihood. Apparently, this was not perceived as a major constraint for performing risk assessments. This indicates that the focus within the scientific community on reducing and communicating uncertainties, which was briefly described in the introduction, might have little impact on the usefulness of research in the direct way by informing decisions through more accurate and precise predictions. However, using state-of-the-art methods and communicating uncertainties have an important indirect impact on usefulness by making the scientific enterprise perceived as legitimate by end users.

In the introduction it was described as an open question when, how and by whom risk assessments should be made: when the quantitative information produced by modelling of physical processes should be transformed to usable knowledge via subjective, value-based, risk assessments. The results of the interviews indicate that this question indeed is a crucial one, but also that it defies simple answers. The range of interpretations and assessments made by decision-makers and experts were quite wide, a result that questions the idea that the risk information is "objective" and can be communicated to a broad group of end-users whom effectively will select and make use of the information. Leaving the task to assess the risks to end-users will lead to misinterpretation and misuse, or perhaps more likely, that the information will not be used at all. An important finding is therefore that risk assessment and dissemination should be a joint effort by end-users and researchers in order to produce actionable knowledge.

6. Conclusions

Risk maps produced by the Climate for Culture (CfC) project show future indoor climate related risks to historic buildings in Europe, based on building simulations of generic buildings. In this paper, a methodology for how to select adaptation-relevant parts of this risk information and pre-test its dissemination was developed in a collaborative effort by researchers and a specific stakeholder group, the Church of Sweden. The major objective of the paper was to understand how heritage decision-makers in the Church of Sweden made sense of the generic, ambiguous and complex risk information produced by CfC, and a secondary objective was the development of the methodology itself. Risk maps produced by the CfC-project were jointly selected by stakeholders and researchers. Twenty decision-makers and five indoor climate experts were interviewed with the aim to understand how they interpreted and made sense of the maps.

The interviews give a new and better understanding of why the risks were interpreted and assessed differently by the respondents. This is shown to be largely dependent on their pre-understanding and familiarity with the individual risks rather than on the information provided. Most interviewees were hesitant about making risk assessments, possibly because of that the information provided weak cues. In turn, risk assessments were dominated by already established notions of climate change and its impacts on Swedish churches. The magnitude of the change and the accuracy of predictions were subordinate to the overall impression of the information as being credible and salient. Multiple understandings and uses of the risk concept made comparisons of the risk assessments problematic. However, the lack of information about the range of uncertainty in the information was not perceived as problematic by most decision-makers.

The major conclusion of the paper is that the results from CfC are likely to be interpreted in misleading ways if the interpretation and assessment are left to the end-users. The dissemination of risk information, also from projects which at the outset have aimed at producing knowledge relevant for end-users, must be both customized and tested for specific target groups in collaborative efforts by stakeholders and scientists. This result is important for guiding further dissemination of results from CfC as well as for future projects aiming at producing usable knowledge for cultural heritage management. By extension, this is also a call for further qualitative research concerning how climate risk information is shared to and acted upon by different stakeholder groups.

7. Acknowledgements

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Paper VI.

Standardizing the Indoor Climate in Swedish Churches: Opportunities, Challenges and Ways Forward

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Abstract

Standardization for indoor climate control in historic buildings has recently taken a new direction with standards and guidelines that focus more on decision processes than outcomes. The objective of the paper is to explore and discuss how standards can evolve to both fit and guide decision processes to facilitate a sustainable management of Swedish churches. Interviews with engineers and heritage professionals in the Church of Sweden in combination with indoor climate monitoring were used to understand the technical and organizational context. The results show that the development of process standards solves some of the problems related to the conventional outcome-oriented approach by opening up for a wider set of solutions. However, available guidelines are difficult to apply and integrate in the existing management of churches. A stronger focus on strategic feedback and an increased use of local guidelines are suggested.

Keywords

Indoor climate control; Process standards; Knowledge sharing; Sustainable management

1. Introduction

The overarching problem addressed in this paper how scientific knowledge and best practices regarding indoor climate control should be shared to end-users in order to facilitate a sustainable management of cultural heritage. The indoor climate is an essential aspect of the management of historic buildings housing cultural collections. The use and preservation of the building and the collection, as well as the financial cost and environmental impact related to energy use are all dependent on the extent of indoor climate control (e.g. BSI 2012). Substantial effort has been devoted by the conservation community to address this issue. The focus has been on the technical aspects and considerable progress has been made in terms of materials science and technical solutions (e.g. Camuffo 2014).

To determine an indoor climate control strategy is oftentimes a complex task, involving social as well as technical dimensions: conflicting objectives have to be negotiated, aspects of management that commonly are separated have to be involved and different types of expertise is needed (Leijonhufvud and Henning 2014). Simple, generic advice is often not sufficient to guide decisions. Hence, the sharing of scientific knowledge and best practices, and their uptake in decision processes are paramount for the implementation of more sustainable solutions. However, the way scientific knowledge is utilized in these processes is poorly understood.

We argue that the issue of knowledge sharing has not been given sufficient attention despite its key role, and suggest that it is an important barrier to improvements of practice. An important means of knowledge sharing related to indoor climate control has been the production and use of guidelines, recommendations and standards1. While there is an on-going debate on the scientific basis for current museum standards (Cassar 2011, Bickersteth 2014), there is little discussion or research about the ways in which standards and guidelines actually are used. Despite efforts to standardize indoor climate control in new ways, there is a shortage of empirical research as well as theoretical discussion about the nature of standardization and the use of standards related to indoor climate control in historic buildings.

Universal advice regarding set points for indoor climate parameters – the "ideal climate" approach – have substantial shortcomings (Erhardt and Mecklenburg 1994, Michalski 2009, BSI 2012, Staniforth 2014). It therefore seems to be wise to produce standards that support decision making, rather than forego it. There is ample evidence that a successful development of decision support presupposes a sound understanding of the decision context, both regarding organizational and technical aspects (National Research Council 2009). The diversity of historic buildings, collections and the ways they are managed imply that the decision processes regarding indoor climate control unfold in myriad ways dependent on the specific contexts. Hence, it is unlikely to find a simple, generic roadmap for the decision process to establish an indoor climate control strategy. In practice, such processes are often intertwined with other planning and management activities (Leijonhufvud and Henning 2014).

Given this background, is there a role at all for standards, which by definition

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1. In the rest of this paper, we use the term standard as defined by Brunsson *et al* (2012, p. 616): "…a rule for common and voluntary use, decided by one or several people or organizations.". This definition includes documents issued by international standardization bodies as well as institutional guidelines and recommendations in handbooks. This is of course a very all-encompassing definition, but it reflects how general recommendations that have not been officially sanctioned still have had major impact on practice.

have to give advice about common problems? A number of recently published standards indicate that there is a shift in standardization both in terms of scope and overall approach, with the ambition to deliver advice customized to the individual situation (Staniforth 2014). As discussed in more detail below, these new standards and guidelines are increasingly influenced by ideas of enterprise risk management. However, previous research has shown that risk management guidelines have to resonate with existing management processes to be effective; otherwise they tend to "live a life of their own /…/ detached from the practical reality of actors"(Boholm 2010, p. 252).

The objective of this paper is to explore and discuss how standards can evolve to both fit and guide decision processes to facilitate a sustainable management. To achieve this objective, we discuss the recent progress in the standardization of indoor climate control for historic buildings in general and the European standardization of the indoor climate in churches in particular. By drawing on the scholarly literature on standardization we identify key issues that both the makers and users of standards have to address.

The church of Sweden is then used as a case study, presented in section 3. The objective of the case study is to identify opportunities and challenges with contemporary standards for churches in Sweden. By combing a qualitative study of how indoor climate control is managed with a discussion of the use of existing outcome-oriented standards in Swedish churches we outline both the organizational and technical contexts in which standards are to be implemented. We hypothetically apply the recommendations given by two different outcome-oriented standards in two intermittently heated Swedish churches located in different climatic zones. This exercise is made to identify the strengths and limitations of the more traditional outcome-oriented approach.

The final section relates the results of the case study with the key issues regarding standardization identified earlier. Based on this analysis, we suggest ways forward for the standardization of indoor climate control in historic buildings.

2. Recent development of standards for indoor climate control in historic buildings

There exists a patchwork of standards for indoor climate control in historic buildings housing valuable collections: recommendations in handbooks, international standards, national guidelines etc. The aspiration of standard makers has generally been to describe safe ranges based on scientific evidence, or, when science has been unable to deliver enough facts, on precaution in combination with practical experience (Brown and Rose 1996). Efforts to specify single, universal, "ideal" targets have been persistent despite "a steady undercurrent of thoughtful critique" (Michalski 2009, p. 1). Overly simplifying interpretations of standards have distorted the original intentions. The famous example is how recommendations in Gary Thomson's textbook The Museum Environment (Thomson 1978) inadvertently contributed to a de facto standard for museums, the so called 20/50 standard (Bickersteth 2014). The development of standards has not been a linear process where accuracy and precision has increased along with the development of scientific knowledge. Rather, there is a great variety in how standards are written, how they are intended to be used and finally in how they actually are being used in practice. The following account point at recent developments in standardization and connects these with findings from a broader scholarly literature on standardization.

An important distinction to keep in mind when discussing standards is between the intention of standard makers and the actual use of standards. There is a process of interpretation and translation to make a standard work in practice, and standards are generally not used as intended by standard makers (Timmermans and Epstein 2010). The history of indoor climate standards tells us that advice or specifications are transformed when applied in practice, and that widespread adoption of standards is not to be taken for granted (Weintraub 2006, Michalski 2009). Furthermore, there is a dynamic between practices and standards in both directions. Brown and Rose (1996) illustrate in their account of the development of indoor climate standards how practices, technologies and recommendations have co-evolved into a de facto standard for indoor climates in museums. This dynamic of standardization is often neglected. Standards and conventions are at times difficult to distinguish, and in practice they tend to reinforce each other (Timmermans and Epstein 2010).

For the purpose of the following discussion, we suggest two different ways in which outcome-oriented indoor climate control standards are used in decision-making. Firstly, there is the *prescriptive use*, where the standard serves as a substitute for decision-making. Planning processes where specifications are needed at an early stage promote this use of standards (Weintraub 2006). Secondly, the standard can be used as *decision support*, supporting the user in a negotiation between conflicting objectives. The standard provides heuristics or tools, but the numbers and thresholds included will be interpreted, negotiated and customized to suit local, specific conditions. A process standard, on the other hand, *provides a roadmap for the decision-making process*. It does not include general threshold or limits, but stresses the importance of making informed decisions in a systematic way.

In the last years there has been an intensified discussion about the optimal set points for T and RH in museums and archives, fuelled by the wish of cultural institutions to become more environmentally sustainable (Bickersteth 2014, Staniforth 2014). Suggestions of T and RH in museums used to be based on precaution and the potential of existing technologies (Brown and Rose 1996, Atkinson 2014). The overarching approach was to identify safe limits for the indoor climate which could be transferred to end users in standards and guidelines. The scientific com-

Class	Climate specification	Collections risk and benefits
C Prevent all high risk extremes	25 < RH < 75% Temp. < 25°C	High risk of mechanical damage to high-vulnerability artefacts; moderate risk to most paintings, most photographs, some artefacts and most books.

Table 1. An excerpt from target specifications of T and RH in ASHRAE 2011.

munity is now increasingly focused on a better understanding of damage functions with the intention to inform evidence-based risk assessment (e.g. Erhardt *et al.* 2007, Bratasz 2013, Strlič *et al.* 2013).

Even though the discussion of set points historically have been, and to some extent still is, focused on "proper" museums, it is relevant for historic buildings housing collections, such as churches or historic house museums. Historic buildings have been treated as exceptions to the rule, which require special treatment. Suggested targets in standards and guidelines for museums and archives have sometimes been perceived as unachievable ideals to strive for. The pragmatic way to address historic buildings in standards has been to widen the allowable climatic range used for museums, accepting a slightly higher level of risk.[2] Such separation of buildings and collections into distinct categories amenable for different levels of climate control is, however, difficult to apply in practice. In a recent Dutch study, there exists a continuum of the level of control of the indoor climate in museums, as well as continuum of the hygrothermal performance of the building envelopes (Martens 2012). A decisive factor decoupled from the building properties is the financial resources for climate control, which are lacking for many smaller museums (Bickersteth 2014).

The more recent development in standardization has been a gradual shift away from definite guidance in the form of universal numbers toward more flexible approaches (Michalski 2009, Atkinson 2014, Michalski 2016). There has also been a shift in scope, i.e. what phenomenon that is to be standardized. In the following, four recently published standards are presented.

2.1. *ASHRAE Handbook*

The major revision made in 2003 of the *ASHRAE Handbook* was based upon a risk based approach to decision-making for preventive conservation, as described in Michalski (2009). The revised standard, as well as its revisions in 2007 and 2011, essentially consists of risk information about different types of deterioration. There is also a table included where target specifications of T and RH are given for different risk levels. The risks and

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[2] Examples are "Class 2" in The Museum Environment (Thomson 1978) and ASHRAE handbook class B, C, D (ASHRAE 2011).

benefits associated with different classes, ranging from AA (best) to D (worst) are summarized in the table. In addition, there is a table called "Classification of Climate Control Potential in Buildings" which links the potential to control the indoor climate with different building types.

As described by Michalski (2009), it was the intention that the ASHRAE handbook should incorporate risk management principles and common knowledge in the field. The information about different kinds of deterioration given in the standard provides decision-makers with tools and heuristics to make trade-offs between risks and benefits. However, the demand of simple and quick advice is also recognized with the provision of a table with target specifications. There is a risk that target specifications are used without much consideration of the discussion in the accompanying text. This was considered in the use of letters for labelling the different classes: it was decided to label the class with the lowest risk AA instead of A, as a way of informing that A is a good enough alternative for those wanting "what was widely seen as optimal" (Michalski 2009, p. 7).

The ASHRAE standard provides risk information and heuristics to support decision-makers as well as target specifications for indoor climate parameters. In doing so, it uses a similar approach as Thomson did in the Museum Environment by summarizing existing knowledge, discussing how it plausibly can be applied in practical settings, and finally suggesting generic advice about target specifications. It emphasizes the negotiability of the end result as well as the limitations given by different types of building envelopes and climatic conditions.

2.2. EN 15757:2010

The European standard EN 15757:2010 *Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials* (CEN/TC 346 - Conservation of cultural property 2010) describes a methodology to establish allowable fluctuations based on the historical climate. It is based on the assumption that objects in the collection have adapted to their environment and that by limiting deviations from the historical climate there will be less risk for further damage (Bratasz *et al.* 2007). In contrast to many other standards targeting the preservation indoor climate, it is exclusively focusing on mechanical damage in organic hygroscopic materials. The method to establish allowable RH fluctuations in EN 15757:2010 is based on the climate history of a specific building. Rather than specifying a constant target level for the whole year or season, this method is based on a moving seasonal average around which variations should be limited. The mean target value for RH is calculated as a moving average over a 30 day period, from measurements for at least one year. The aim is to eliminate harmful fluctuations in relation to the historical climate. A fluctuation from the seasonal average is considered outside the safe range when the magnitude is more than 1,5 standard deviation. However, the standard says that the target range never has to be less than ±10 %.

1. Assessment of building interiors
2. Specifications of indoor climate
3. Determine heating strategy
4. Determine heating system
5. Implementation
6. Evaluation

Figure 1. EN 15759-1:2011. Rather than specifying an expected end-result, this standard describes a decision process which aims at identifying an appropriate solution for the individual case based on a compromise between comfort and conservation requirements.

Previous standards have based recommendations on a compromise between different deterioration mechanisms and different materials (e.g. Erhardt and Mecklenburg 1994). EN 15757:2010 deviates from this approach by concentrating on mechanical damage and hygroscopic, organic materials. The standard opens up for a wider range of outcomes by taking the specific conditions of the individual building as the point of departure. However, it is unclear if adhering to the standard actually implies a certain allowable band or if the focus is to present a systematic method to determine dangerous fluctuations based on the historic climate.

2.3. EN 15759-1:2011

The limitations of standards that attempts to give universally valid recommendations about outcomes have resulted in a development towards standards that focus on the decision process. An example is the European standard EN 15759-1:2011 *Guidelines for heating of churches, chapels and other places of worship (CEN/TC 346 - Conservation of cultural property 2011).* The standard describes in its first stage a process for how to establish a target indoor climate, but does not suggest any numbers. In essence, it describes a procedure that needs to be followed rather than suggesting the outcomes. In the following stages, the standard describes how to identify appropriate climate control strategies and technical solutions.

2.4. PAS 198:2012

The recent UK PAS 198:2012 *Specifications for Managing Environmental Conditions for Cultural Collections* (BSI 2012) lays out a framework (fig. 2) representing a risk-managed, holistic approach to environmental management (Bickersteth 2014). It is emphasized by the standard how universal ranges for RH or T cannot be established, based on their different dependencies on various deterioration mechanisms. The balance of different objectives (stability, cost, sustainability, and accessibility) forms the core of the standard (Ashley-Smith 2016). For example, it is pointed out how "a universal safe zone for all collection items" can result in "unjustifiably increased use of energy" (BSI 2012, p. 9). The standard does not suggest target specifications but it is, in the same way as the ASHRAE handbook, accompanied by a summary of existing knowledge regarding damage functions in an informative annex. The scope of this standard is somewhat broad-

1. Assign responsibility
2. Develop a strategy
3. Collect data
4. Assess the risks
5. Set an environmental specification
6. Monitor environmental conditions
7. Achieve energy economy
8. Document and retain data

Figure 2. The overall framework in PAS 198:2010 for developing an environmental management strategy and setting an environmental specification for a collection.

er than the ASHRAE handbook or EN 15759-1:2011: it includes both the overall management process and the decision process to determine target specifications.

2.5. The dilemma of standards: Generic advice for specific needs

A dilemma pertinent to all standardization is to find the right balance between firm advice and flexibility. This dilemma originates in the basic condition that a standard is general whereas practice is specific (Timmermans and Epstein 2010). Experience from how standards are used in practice show that more loosely defined standards with greater adaptability may work better than rigidly defined standards (Timmermans and Epstein 2010). This might be particularly relevant for conservation practice. The problems to be solved by conservation practitioners call for approaches where the unique characteristics of a place guide decision-making (Mason 2002, Muñoz Viñas 2005). Standards, which by definition aim for some kind of universal guidance, can therefore prove difficult to apply in a strict way (Alcántara 2002). This is a challenge pertinent also to indoor climate control standards for historic buildings, as the demands on the indoor climate varies widely between different buildings, not only due to technical differences, but also due to differences in how buildings and collections are used and valued (Leijonhufvud and Henning 2014).

A possible way out of this dilemma is to standardize organizational processes instead of end-results. To separate between these two types of standards, we use the distinction suggested by Brunsson *et al* between *outcome standards* and *process standards*, where the former require the user to deliver a certain outcome, and the latter is intended for standardizing organizational processes (Brunsson *et al.* 2012). We suggest that there have evolved two separate ways of making indoor climate standards more flexible. The first approach has been to develop more sophisticated outcome standards that are targeting specific problems and open up for more elaborate risk assessment procedures, the second has been a shift towards process standards. The production of EN 15759-1:2011 and PAS 198:2012 are representative for the latter, with a standardization of processes instead of outcomes. The analytic separation between outcome and process standards is in practice not straightforward, rather the two approaches complement each other and one standard can contain elements of both. For example, the use of EN 15757:2010 is referred to in the decision process outlined by EN 15759-1:2011. PAS 198:2010 is accompanied by "notes and informative annexes" to inform risk assessment. ASHRAE handbook contains elements of advice about a structured decision process. In sum, these two approaches to make standards more flexible are in practice not distinctly separated, and in the four standards presented above there are variations of both.

While EN 15759-1:2011 and PAS 198:2010 both aim to standardize processes, they have a somewhat different scope. EN 15759-1:2011 is targeting the decision process needed to determine a target indoor climate and the implementation of technical solutions. It is implicit that this is a one-shot decision rather than a continuous process. PAS 198:2010 has a slightly different scope. It targets the continuous management of the indoor climate by addressing issues of responsibility, strategy development and documentation. The setting of specifications is one step among others, and the incorporation of the standard with existing management processes is mentioned. The focus on processes in EN 15759-1:2011 and PAS 198:2010 is promising as it opens up for a wider set of solutions, better customized to specific situations. However, process standards bring a new set of challenges.

2.6. The need for complementary knowledge

Process standards are widely used for quality management and for managing risks in organizations. They generally do not require compliance with an objective or a specific result. Instead, they standardize procedures, duties and roles (Heras-Saizarbitoria and Boiral 2013). The requirements of such standards are abstract and generic to the extent that almost any organization can adopt them (Testa *et al.* 2014). The obvious drawback with process standards is that an adoption of the standard does not guarantee desirable consequences. Knowledge and best practices have to be transferred to the user of the standard via complementary sources. The user has to rely on these sources in order to assess the consequences of different courses of action. To achieve desirable end-results regarding indoor climate control requires a well-organized collaboration of qualified professionals whom have access to guidance focusing on specific expert knowledge.

Absolute and easily digestible guidance is demanded in many practical cases, where the management organization is lacking the competences and resources needed to successfully use the standard. In this context it means that a non-qualified user may come up with technical solutions that are completely inappropriate while still adhering to a process standard. This problematic situation is emphasized in the ASHRAE handbook (2011, pp. 21.5): "No two collections are identical. /…/ Experienced experts are best equipped to identify areas of special risk and devise solutions, and to properly manage economic and other trade-offs, although this level of expertise is not always easily available". A possible remedy to this dilemma is to link process standards with outcome standards, an approach that is increasingly common in other domains of standardization (Brunsson *et al.* 2012).

2.7. The logic of decisions: risk- or rule-based?

The decision logic implicit in standards is generally rule-based (Brunsson 2007). Standards typically offer rules for situations of choice. The decision process is essentially about identification; to find the appropriate rule for a given situation. Process standards deviate from this approach in that they encourage the user to frame decisions as a matter of optimizing costs and benefits. In doing so, it is taken for granted that the user of the standard is capable of estimating consequences, coping with uncertainty and making trade-offs. Decision support tools encouraging the use of such consequential logic are implicitly anchored in the view that decisions should be what March (1994, p. 97) calls "intendedly rational choices", where benefits and risks of different alternatives are evaluated. The predominance of such consequential logic is inscribed in various forms of formal risk management protocols which are increasingly used for organizational governance (Power 2007).

The idea that decisions in organizations are and should be intendedly rational choices is both appealing and pervasive (March 1994, Langley *et al.* 1995, Brunsson 2007). In the conservation field, the idea resonates with the contemporary emphasis on quantitative risk assessment as a foundation of conservation decisions (Ashley-Smith 1999, Waller 2003), as well as the increased demand on conservation decisions to be transparent and evidence-based (Jones and Yarrow 2013). There are, however, reasons to be cautious as practitioners might be reluctant to use formalized decision frameworks. Risk management in organizations tends to be intuitive and experience based, despite efforts to formalize it (Boholm 2010). Experiences from the construction sector show how practitioners base their decisions on previous experience and current practice rather than formal decision tools and management control systems (Gluch 2005). These experiences suggest that the key question is if standards which require risk-based decision making are powerful (and digestible) enough to rectify existing decision processes to the extent that informed risk/benefit trade-offs will substitute conventions and simple rules.

The turn away from a rule-based logic of decision-making towards the consequential logic implicit in process standards is challenging as it requires a high level of competence of the user. A related phenomenon is that process standards are more or less void of value judgements. The setting of performance targets or risk thresholds is always based on judgements about values (Funtowicz and Ravetz 1993, Stirling 1998). This implies that an adoption of a process standard has to be accompanied by a discussion of values and take as departure the objectives of the collecting organization. If the objectives and values of the organization are diverging from those of society as a whole, there is a risk that sustainable solutions are not achieved even though the standard is implemented (MacDonald 2005).

Finally, the use of process standards might result in more paper work than action. There can be many different rationales for adopting a standard, and if a standard is not perceived by the user primarily as a tool for achieving improvement of internal practices its use might not lead to any significant changes (Brunsson and Jacobsson 2000, Alcántara 2002). There is a risk that standards are used as labels for demonstrating the accountability of the organization in the view of external observers, for example funding bodies. This might lead to new administrative processes and changes in discourse, with little impact on practice (Power 2007).

2.8. Summing up the recent development: challenges with process standards

The multiple forms and ways of using standards discussed so far point at a basic dilemma, where end users expect general and clear cut advice, whereas the complexity of the problem requires individual solutions based on risk assessment and negotiation of objectives. Standards have evolved from simple prescriptions of universal specifications to become more sophisticated, informative and flexible. The scope of standards is shifting: there is a tendency to standardize processes on behalf of outcomes. However, the lack of testing and evaluation of how standards are used suggests that this development emerges mostly from a lack of success with former approaches. There is therefore a need to advance the understanding of the role of standards as decision support tools. To become useful, process standards have to be complemented with both expert knowledge and value judgements. They require more resources to be implemented than outcome standards but promise improved end-results. If the organization adopting the standard lack the resources needed for a successful use of a process standard, it might not lead to improvements.

3. Case study: Indoor climate control in Swedish churches

The Church of Sweden owns and manages, in total, 3384 churches, of which 2976 are protected by the Cultural Heritage Act because of their cultural heritage values[3]. In most of these churches there are conflicting objectives associated with indoor climate control. The use of a church has to be balanced with objectives for preservation, on an oftentimes tight budget. Interestingly, there are no national standards or recommendations for the indoor climate formally endorsed by the Church of Sweden. Arguably, the organization should therefore have a potential to improve building management by using indoor cli-

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[3] In the rest of the paper, the term Swedish churches will refer to churches in Sweden built before 1940 and owned by the Swedish church.

mate control standards. Considering this situation there is a timely opportunity to discuss the recent development of indoor climate control standards from the viewpoint of the organization as a whole.

Both the technical and organizational contexts are outlined in order to understand the needs and challenges of improved indoor climate control. The following section uses two Swedish churches as examples to illustrate the challenges with the application of existing outcome standards to determine climate specifications for historic buildings. In the next section, we outline the organizational context in which decisions about indoor climate control are made within the Church of Sweden.

3.1. Challenges with outcome-oriented standards to determine climate specifications

In this section we discuss the application of two outcome standards (ASHRAE handbook and EN 15757:2010) in two Swedish churches, Jukkasjärvi in the north and Atlingbo in the south (fig. 3). We derive target specifications from the standards, and then discuss the practical consequences from a hypothetical implementation of these targets. The objective is to investigate the use and applicability of different types of standards rather than trying to compare or evaluate them.

The ASHRAE handbook, which is widely used internationally, and the European standard EN 15757:2010 were chosen as the two most relevant standards based on their applicability for northern climates together with their wide scope that include buildings with limited potential for control. Both standards are briefly presented in section 2 of this paper. The determination of target specifications from these standards demands some degree of interpretation by the user, and we have carefully sought to use the standards in a plausible way.

For the ASHRAE handbook, climate control class C is used. This class is suggested for buildings with no other climate control than heating and ventilation. The target specifications of class C suggests that RH should be kept between 25-75 % at all times. T should be kept below 25 °C. These ranges are supposed to prevent high risk extremes in terms of mechanical damage and biodeterioration. When applying EN 15757:2010, we have used the calculation to determine allowable ranges for RH and T suggested in the informative annex A of the standard. It is not clear in the standard in which cases this calculation should, or should not be used. A major difference between the standards is that EN 15757:2019 exclusively targets mechanical damage to hygroscopic materials, while ASHRAE handbook covers all types of damage.

Figure 3. The location of Jukkasjärvi and Atlingbo churches.

3.2. Jukkasjärvi church

Luleå Diocese is situated in the extreme north of Sweden. During 2009-2011 the indoor climate and energy use in 50 churches in Luleå Diocese were monitored.

The churches in the Diocese illustrate how the indoor climate is affected by the climatic conditions in northern Sweden, which is characterized by long and cold winters. The extremely dry indoor climate resulting from heating makes it difficult to use common recommendations for the indoor climate. As in the rest of Sweden, there are no common recommendations used neither for temperature nor relative humidity for the churches in Luleå. In practice, the temperature during services varies from church to church in an interval from 12 to 22 °C. In Luleå Diocese some churches are permanently heated, some intermittently heated and some are not heated at all and therefore not used during winter. All churches that are heated for services during winter become extremely dry with RH in the middle of the nave often going below 10%. The monitoring campaign suggests that comfort has been the overriding priority in most churches and preservation of the building and the artefacts have been more or less neglected in the design and operation of heating systems. We have chosen the church of Jukkasjärvi as a specific example, but the general argument in relation to indoor climate control is representative for all heated churches in the Diocese.

Jukkasjärvi church is a wooden church built in 1726, located near the 68th latitude, se fig 3. The church is intermittently heated, and in between heating occasions there is a base heating to a constant level. Fig. 4 shows temperature and relative humidity over a year in Jukkasjärvi church. It is characterized by moderate short term variations and substantial seasonal variations of RH in an interval between 5 % and 65 %. The temperature is kept at a minimum of around 7 ºC and during services it is raised to around 21 ºC.

The outdoor climate during winter in combination with comfort requirements makes it unfeasible to comply with the ASHRAE class C recommendation to avoid RH below 25 % in order to reduce the risk for mechanical damages. The only

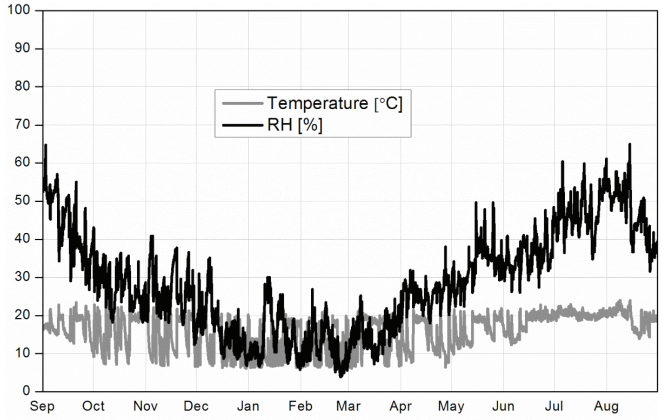

Figure 4. Temperature and relative humidity data from the period 2009-09-01 – 2010-08-31 in Jukkasjärvi church. The logger was situated in the middle of the nave.

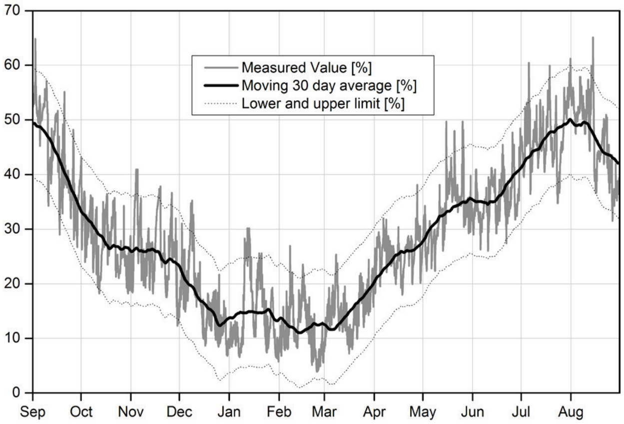

Figure 5. Allowable band of RH fluctuations according to EN 15757:2010 in Jukkasjärvi church. RH data from the period 2009-09-01 – 2010-08-31. The logger was situated in the middle of the nave.

viable option for maintaining relative humidity over 25 % would be to dramatically reduce temperatures, well below comfort levels, or to use humidification. Humidification would cause secondary risks associated with condensation in the building envelope. Therefore, to use 25 % relative humidity as a lower limit in Jukkasjärvi church or the other churches in the Diocese would compromise the use of the church as a place for worship and thereby threaten the main condition for its long-term preservation. The upper limit of 75 % RH is not a problem for this church.

EN 15757:2010 is focused on RH- and T-fluctuations in relation to mechanical damages. The historical climate is used to come up with an allowable band for short-term fluctuations which reduces the risk for further damage to hygroscopic materials. In fig. 5 the suggested method in EN 15757 has been used to determine the allowable band of RH for Jukkasjärvi church. The lower and upper limits are calculated as ± 10 % from the moving 30-day average. There are a number of short term departures from the target range related to the intermittent heating. When the church is heated, RH drops and when the church cools off, RH rises above the upper limit due to moisture released from the building envelope or visitors during services. As these excursions from the “allowable band” are few and modest, only small changes to the current indoor climate are needed. The excursions could be mitigated for example by reducing the heating, prolonging the period for cooling off and/or increased ventilation after services.

However, the benefits for preservation of reducing the small excursions over the allowable band are difficult to assess. To implement the allowable band as a target indoor climate is in a practical case rather complicated. The allowable band has to be translated into thresholds for T and RH, which is not a trivial task given its dynamic character. This translation requires engineering competence as well as insights to the rationale behind the standard.

For Jukkasjärvi church, an obvious drawback with the method suggested by EN 15757:2010 is that long-term fluctuations or absolute levels are not considered risky. There are caveats about these issues in the standard, but to take these into account requires a high level of competence from the user of the standard.

The yearly fluctuation of RH is not considered when calculating the allowable band. This fluctuation in Jukkasjärvi church is exceeding 50 % in the extremely low region of RH. The coefficient of expansion in many hygroscopic materials is greater in this lower region, which increases the moisture related strain in objects in comparison to fluctuations in the mid RH region (Bratasz 2013). Clearly these long-term fluctuations pose a significant risk for mechanical damages, although most damage would already be evident as the current heating regime has been in place for several years. Heating buildings in the cold, Nordic, climate will always result in large seasonal cycles of RH, unless humidification is used. Interestingly, in a study by Silva *et al* (2014) almost the opposite is argued: that the focus on short-term fluctuations makes the standard difficult to apply for buildings in *temperate* climates. It is argued that this is because the standard is based on studies made in a cold climate, and that this justifies its emphasis on short-term fluctuation over seasonal fluctuations.

To sum up the use of the two standards in Jukkasjärvi church, it can be concluded that the specifications suggested in the standards should not be used without modification. In the case of the ASHRAE handbook, the lower limit of 25 % is not feasible in a heated church in northern Sweden. The application of EN 15757:2010 would only require small changes to the indoor climate, but a sophisticated control system is needed. The benefits of adhering to the standard are likely small and difficult to assess, while the major threat for mechanical damages, in this case the yearly fluctuation of RH, is not considered.

The main priority for the churches in Luleå Diocese, Jukkasjärvi church included, is not preservation – it is about how they can continue to be used as places of worship given the cost for heating. A damage survey was made in conjunction with the measurement campaign and the results did not show that the existing indoor climate had a major negative effect on the painted interiors (Brunskog 2012). This does not imply that preservation is or should be neglected, but it is one objective among others in the decision process.

The climatic conditions in Luleå Diocese are far off any of the common notions of a ‘normal’ relative humidity level for preservation. General recommendations for collections, as those developed for museums, have not been considered applicable. This does not imply that there is no potential for improvement; the question is how standards can be designed and used to realize this potential.

3.3. Atlingbo church

There are 92 medieval churches on the island of Gotland in the Baltic Sea around the 57th latitude. A few of these churches are permanently heated, but most are intermittently heated during winter. Atlingbo church is used as an example of problems related to intermittent heating in a humid stone church. The indoor climate for one year is shown in fig 6. The church was heated on around twelve occasions during the year, with no or little base heating in between. The indoor climate is characterized by strong short term fluctuations caused by the intermittent heating and a moderate yearly variation of RH. RH is above 70 % during summer and slightly lower during winter.

The application of the specifications from ASHRAE handbook requires no action in the lower range, as RH is never near the lower limit of 25 %. The indoor climate is often above 75 % for extended periods which points at a risk for mould and insects. Dehumidification or conservation heating would be needed in order to reduce RH below 75 %.

The target range proposed by EN 15757:2010 is also shown in figure 6. The intermittent heating causes a number of excursions well below the suggested range. Hence, a compliance with the standard would limit the possibility of intermittent heating, which is currently considered a feasible heating regime for this church given its use and the cost for heating. To reduce the short-term fluctuations would most likely reduce the mechanical damage to artefacts in the church, but this has to be weighed against the expectations of thermal comfort and the financial situation of the parish.

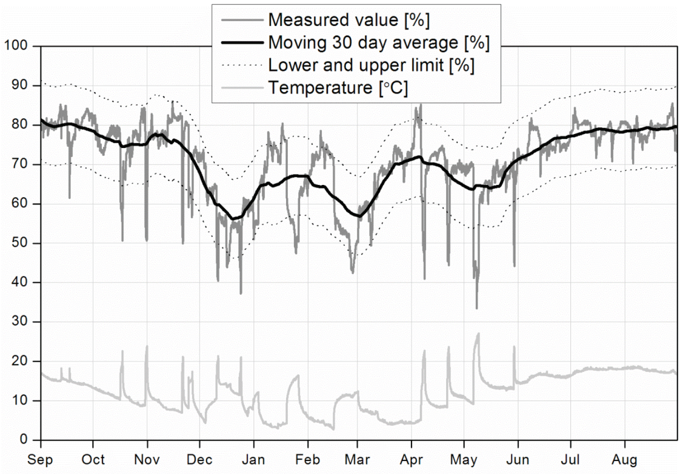

Figure 6. Temperature, relative humidity and allowable band of RH fluctuations according to EN 15757:2010 in Atlingbo church. Data from the period 2009-09-01 – 2010-08-31. The logger was situated in the middle of the nave.

3.4. Outcome standards require interpretation and thoughtful application to be useful

The ASHRAE handbook and the method suggested by EN 15757:2010 are different in the approach and scope, but from an applied point of view they complement each other. ASHRAE provides absolute limits in the high and low range whereas the other method focuses on reducing short term variations.

The application of the ASHRAE specifications is straightforward and does not presuppose any knowledge or experience from the user. However in the northern church its application would not be reasonable. In the southern church, the ASHRAE guidelines point at a serious problem, biodeterioration, which has to be addressed. The application of EN 15757:2010 requires a certain level of technical competence of the user to calculate the allowable band. Furthermore, to control the indoor climate in order to always stay within the allowable band is a complex task. In the case of the northern church an implementation of the standard would not mitigate the most obvious risk for mechanical damage, the yearly fluctuation. In the southern church, an implementation would not be feasible considering the demand for thermal comfort in combination with a lack of money.

In conclusion, we have two cases where a strict application of a standard would be inappropriate (ASHRAE handbook in the northern church, EN 15757:2010 in the southern church). To sum up these two hypothetical cases, we make the following observations applicable to both standards:

- The user has to determine when the standard is applicable and for what purpose. A standard cannot be used bluntly.

- The user has to be able to decide how the standard should be used, modify it based on the requirements of the specific situation and judge if the benefits of an implementation outweigh the costs.

- The standards will be most useful if used as decision support rather than as prescriptive formulas. Especially EN 15757:2010 seems to be most useful as an arithmetic tool useful for identifying risky fluctuations.

A lesson drawn from this is that universal guidance regarding the indoor climate always has to be used with care. It has to be adjusted to the specifics of the local context in order to be useful for effective decision-making. We suggest that the experience that standards should be chosen and used with care is not specific for ASHRAE handbook and EN 15757:2010, but generic. The following analysis point at some explanations to why this is the case. To start with, we acknowledge that there are knowledge gaps. At the general level, there will always be difficulties related to the complexity and uncertainty of the damage functions on which outcome standards are based (Leijonhufvud *et al.* 2013, Strlič *et al.* 2013). However, we suggest that the main difficulty is caused by three key aspects which go beyond the technical issues.

First, the setting of thresholds for what is acceptable is a subjective and value-laden exercise. An irreversible change in an object does not necessarily correspond to a loss of value, and there are good reasons to separate these concepts (Ashley-Smith

1999). Consequently, standards suggesting limits to reduce risk for damage can hardly be derived by science alone. This is a phenomenon that is pertinent to all kinds of regulation about risks (Funtowicz and Ravetz 1993, Gregory *et al.* 2006, Millstone 2009). In essence, the judgement of what is unacceptable should be a matter for decision-makers and stakeholders, not a virtue of scientists. Hence, outcome standards incorporate value judgements which might be concealed for the user of the standard.

Second, there are in practice always compromises and trade-offs needed between different aspects of indoor climate control. Such compromising makes it difficult to use outcome standards where many aspects already are taken into account (such as the ASHRAE handbook where the specifications are based on a mix of deterioration processes). In for example the Jukkasjärvi case, the major trade-off is between use of the building, mechanical damage and energy use which leaves room for a range of possible outcomes. In Atlingbo church, the main threat is biodeterioration. To handle these trade-offs between different objectives requires that outcome standards support the user in estimating the impact of different indoor climates on the collection. An implication of this is that outcome standards will complement, rather than substitute, other sources of risk information.

Third, the weight given to different factors determining indoor climate control, such as preservation, use and resource use, varies between the studied churches. This variation in how the indoor climate is controlled is not only due to physical characteristics of the buildings or the collections, but also to cultural and social factors, manifested in norms and practices specific to the place. Consequently, such variations are difficult to incorporate in generic outcome standards.

The case studies illustrate how the seemingly simple adoption of plausible science based recommendations to improve the indoor climate becomes a difficult undertaking in practice. While we acknowledge that it always is possible to find single cases which represent anomalies in relation to general advice, and that such advice cannot be properly evaluated on the basis of individual cases, we suggest that the case studies illustrate universal problems, rooted in the fact that the benefits derived from indoor climate control are valued quite differently from case to case. As mentioned above, the notion that universal guidance is problematic, especially for historic buildings, is not new. These examples add an explanation of the problem which goes beyond the mere technical issues.

4. The organizational context of the management of Swedish churches: opportunities and challenges for future standardization

The Church of Sweden was formally disconnected from the State in year 2000. The building management organization is highly decentralized. The responsibility to manage each church lies on the members of the individual parish. Many parishes have recently merged into vicariates consisting of multiple churches, partly due to the decreasing number of members and a decrease in the use of churches. The management is to a large extent organized as a decentralized layman-led activity, both regarding decision-making and practical work. The benefits and drawbacks of this situation are continuously discussed within the organization. One side argues that the management should be more professionalized in order to become more effective, the other side stresses the importance of local involvement, involving the members of the parish in decisions and daily duties (Svenska kyrkan 2015).

The status of churches as cultural heritage implies both legal protection and financial support from the state. All major changes to churches built before 1940 have to be made in accordance with the Cultural heritage Act. All such changes require permission from the County board. Furthermore, there is a considerable amount of money (ca 50 million Euro per year) provided by tax payers for the preservation of churches. This funding scheme is central for the upgrading and installation of new climate control systems in churches.

Swedish churches in general house and display valuable and fragile works of art, ranging from medieval to contemporary. Despite this fact it is clear that the preservation aspect has had much lower priority as compared to most museums. This is rooted in a historical conflict between the Swedish church and Swedish heritage authorities about the status of churches as cultural heritage and/or places of worship. Thus the expectation on how churches are used is twofold - as a place of worship and as cultural heritage.

Swedish churches have been heated for a little more than a century (Legnér 2015). The indoor climate control strategies have generally been decided in ad hoc compromises between cost and comfort, partly because of a lack of appropriate guidance. Decisions and interventions have not been well documented, or available documentation has not been used which has led to a repetition of errors (Legnér 2012). There has been little systematic use of feedback to improve the overall control strategies.

To further the understanding of existing decision processes regarding indoor climate control in the churches, as well as the role of standards in these processes, we conducted interviews with a group of professionals employed at the Diocese level. The individuals in this group consist of engineering and heritage professionals employed to support parishes with all aspects of the management of churches.

Typically, there is one engineer and one building conservator employed by each of the thirteen Dioceses. In total, twenty interviews were made with engineers and building conservators employed at the Diocese level in the Swedish church. The interviews were made over telephone in August-September 2014 and lasted about one hour each. Survey questionnaires were sent to the interviewees beforehand. This questionnaire consisted of questions related to indoor climate control and indoor climate related risks. The most important question was a broadly phrased question about barriers and drivers to improved indoor climate control in churches. All interviewees were probed to discuss the role and usefulness of standards, irrespective if they were used in the Diocese or not. The interviews were recorded and notes were taken during the interviews. Selected portions of the recordings were transcribed.

Organizational deficits, inadequate decision processes and a lack of in-house expertise were described as the most important barriers to improved indoor climate control by the interviewees. Organizational deficits were often mentioned in tandem with a lack of professional competence within the organization.

Generally there is an organizational division between continuous daily management and more infrequent projects in relation to major changes of control strategies and/or technical systems. The organizational and financial framework favour that major changes of indoor climate control systems are made as part of a package of other renovation or conservation work. In these projects there is a different set of actors involved than during daily management.

A change in control strategy or the installation of a new technical system is a one-shot decision for the individual parish. This is how one engineer described this problem:

> A management perspective is lacking, there are not enough managers and competence is missing within the church. One-time clients [Swe. engångsbeställare] dominate today and that is not good at all. Management is about doing things over time and it is not only about technical things. (engineer)

This status of parishes as one-time clients with limited competence is a cause of a weak position in relation to contractors. This leads to problems with the acquisition of new technical systems as pointed out by a building conservator.

> The combination of lacking procurement skills, lack of guidelines and overconfident contractors leads to many problems with new installations. (building conservator)

The decentralized structure and the division between daily management and one-shot knowledge intensive projects make it difficult to systematically use feedback for continuous improvement and knowledge sharing. There is no systematic connection between the permanent organization responsible for daily management and the temporary organization that emerges in connection with renovation projects. The feedback loop between these two is weak or non-existent. This results in a problem with knowledge sharing within the organization as a whole.

Most churches have a maintenance plan, but indoor climate control is generally not included in these. Almost all dioceses had finished or on-going projects which were aimed at surveying conditions in the churches related to the indoor climate, but there was a difficulty to get sufficient resources for these projects, especially in the long term due to organizational and funding constraints. The usefulness of these projects was however unanimously acclaimed by the interviewees.

> Now when we have made this comprehensive survey [of the indoor climates in the churches of the diocese] , we can look back at it and distinguish long term changes. This was not possible before: to know the starting point is very important. (engineer)

Only one of the interviewees reported that indoor climate standards were used in a deliberate or systematic way. The most common rationale for the unwillingness to use standards was that they were perceived as too general and not customized for churches. Handbook recommendations found in the conservation literature, even those intended for historic buildings and churches have been so far away from the actual conditions in the churches that they have not been perceived as realistic.

The present situation, with a lack of systematic decision making, can to some extent be explained by a complex decision context with conflicting views on the use of the churches and many stakeholders at local, regional and national level. It is not clear where the responsibility for strategic planning of the indoor climate is or should be. As a result, there has been no systematic evaluation of the indoor climate in the churches. Problems have been dealt with on an ad hoc basis.

Based on the above analysis we argue that there are three major issues for the Church of Sweden in relation to standardization:

- The management processes for daily operation and renovation of indoor climate control systems are decoupled. Standards for indoor climate control have to address both processes, link them together and integrate them better with the regular management of churches.

- A lack of evaluation and feedback regarding indoor climate control is evident at both the level of individual churches, as well as on aggregated levels.

- There is a need for simple and unambiguous advice to support parishes. The lack of competence and lack of resources make demanding decision processes unattainable.

5. Discussion and ways forward

The review of recent standards for indoor climate control in historic buildings in combination with the results of the case study demonstrate that neither is the scope for indoor climate standards a priori given, nor their role in decision-making. The case study showed how outcome standards, used in a prescriptive way, may cause more problems than they solve. At the same time, there are not enough resources or competence available in the Swedish church to make customized, risk-based, decisions about target specifications and technical solutions for individual churches. Is there a way out of this dilemma, and what roles might standards play? Based on the review of recent standards and the results of the case study we suggest the following ways forward for standardization:

5.1. *A landscape of standards*

For long, the purpose of an indoor climate standard was undisputed: to recommend targets for the indoor climate. Some recent standards, acknowledging the complexity of the problem, are deviating from this approach by focusing on decision processes. Instead of debating if one approach is superior to the other, standard makers and users of standards should embrace the idea that standards with different scopes can be used in parallel to serve different purposes at different levels of abstraction (van Gigch *et al.* 1996). At the top level there can be management standards that define processes, duties and roles for the long term management. The decision process to come up with target specifications and technical solutions could be the scope of another standard. Outcome standards focusing on various damage functions could be used as decision support tools, complementing other sources of risk information. Finally, there will probably always be a demand for standards that give simple and universally applicable advice. We suggest that there is a need for all these kinds of standards; the question is when and how to use them. The idea of such a landscape of standards opens up for the individual standard to be more specific about its scope, and thereby more focused.

5.2. *A focus on feedback*

The concept of continuous improvement is a core feature of quality management (ISO 2009). Brouwer and Coppen (2008) have showed the importance of differentiating between strategic and tactical improvement when defining continuous improvement in management standards. Strategic improvement is about defining, implementing and evaluating the overall strategy. Tactical improvement considers the fine-tuning of operational processes. A lack of strategic improvement leads to sub-optimization and in the end to a departure from basic principles for sustainability (MacDonald 2005).

A problem evident in the management of Swedish churches is the lack of systematic evaluation of parameters with relevance for the objectives of indoor climate control. If evaluation of indoor climate control systems are performed, it is almost exclusively to evaluate whether the indoor climate is in accordance with specified targets (tactical improvement), not whether the targets are the right ones (strategic improvement). This results in a situation where technical systems and control strategies are implemented, but it is not known if the consequences of the implementation are in line with strategic objectives such as energy use, preservation and use of the building.

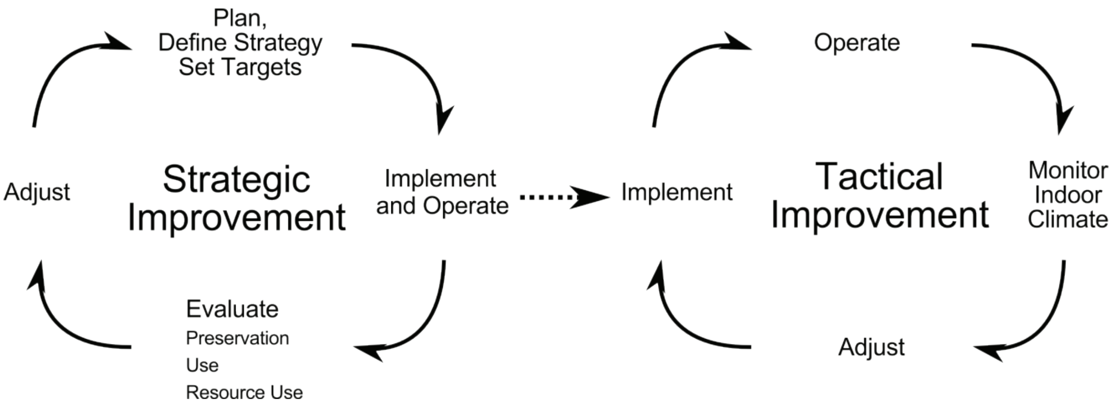

Fig. 7: The two levels of continuous improvement for indoor climate control.

We suggest that indoor climate control in Swedish churches should focus more on strategic improvement, and that this approach should be acknowledged and supported by standards. Tactical improvement should be part of any indoor climate control system already and it is also a part of standards today. In order to achieve strategic improvement there is a need to use feedback of relevant parameters. We suggest that the addition of such feedback loops is both necessary and possible, and that the main feedback needed is about preservation, use and resource use. Strategic and tactical improvement for indoor climate control and their respective feedback loops are illustrated in figure .

5.3. Local guidelines for local needs

Process standards require professional competence, resources and an organization that is not available in most Swedish parishes. There is, however, a potential to use process standards at a higher level in the management organization. For churches which are similar in construction, use and geographic location there is a potential to use process standards to establish local guidelines for the set of churches in question (for example at the Diocese level). This simple solution could help to overcome the problem that process standards are time and resource demanding in their implementation. It may not be feasible to go through all suggested steps in a process standard such as EN 15759-1 for every Swedish church. However, there is an option to use a process standard to establish common advice regarding set points for a specific type of church, within the same climatic zone, with similar use and demands for thermal comfort. In reality such local praxis is already used in many Dioceses but it is not formalized and used in a systematic way. This approach would overcome some of the problems associated with the production of individual guidelines for each building which, given the decentralized management of Swedish churches and the lack of resources, almost certainly would fail.

5.4. *Evaluating standards*

We have pointed out that the recent development of process standards may solve some of the problems related outcome standards. However, new challenges arise. It is not known what the impact will be of these new standards, and consequently there is a need to evaluate how they are used and the consequences that follow. The review of recent standards and the case study point at the need for and means of further research on how standards are used and implemented. A feedback loop at the strategic level could provide input for a third level of continuous improvement, that of evaluating and improving standards and guidelines.

Standards and guidelines are and will be an important tool for quality assurance in cultural heritage management. We have tried to point at some possible areas of improvement relating to indoor climate control of Swedish churches. However, the issues raised in this paper have bearing on other areas of cultural heritage management subjected to standardisation. While there is a discussion about the scope and role for standards in conservation, there is a lack of empirical knowledge on how standards actually are used in conservation, how they affect practices and the organizational processes that forms the infrastructure for decisions. The intensive work currently going on in national and international standardisation bodies needs to be paralleled by a reflexive debate within the conservation community about the role of standards and guidelines, as well as empirical research targeted on understanding the dynamics of knowledge and technology transfer.

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