BARRIERS LEADING TO BUILDING SERVICES OVERDESIGN

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ABSTRACT

The research of this paper provides a useful insight into the many barriers leading to building services overdesign, within the context of NHS hospitals. The issue of overdesign in building services is a systemic problem, whereby numerous contributing factors manifest into an issue that inevitably leads to poor system performance and excess costs. A key factor leading to oversizing is the excessive and uncoordinated application of design margins across the various stages of a building services project. Poor communication between project stakeholders is another significant barrier that inhibits the distribution of information between design groups; unknown requirements, system redundancy and poor system specifications further add to the problem. There are many complex interrelationships associated with the building service design process in hospitals, with external stakeholders adding to the complexity. This points to the importance of effective communication between stakeholders and clear contractual terms between NHS Trusts and external private sector organisations. Many of the barriers identified within this paper are by no means limited to building service systems but also impact on a range of other engineering disciplines.

Keywords: Overdesign, Case study, Design practice, Communication, Building Services

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1 INTRODUCTION

Building services design is a specialist, complex and multi-layered engineering process that requires specific data, information and direction from the commissioning organisation, usually by way of a client brief or design specification. This practice also relies upon the expertise of the engineering design team to make well informed decisions and assumptions based on best practice and past experience. Many of the design decisions made are based on intuition and heuristic 'rule of thumb' principles, however, there is a tendency to 'err on the side of caution' when choosing the operational capacity of plant, ensuring that any equipment selected is not at risk of falling short of the building peak load requirements. This cautionary approach very often leads to oversized building service systems that are incapable of operating at their optimum efficiency point.

Oversized systems are a greater problem in some applications than in others. Some building service systems have low energy requirements such as fire detection and alarm systems, information and communications technology, security systems and building management system (BMS) controls. Others such as heating, ventilation and air conditioning (HVAC) systems are very energy intensive, consuming between 30 to 40% of the total building energy consumption within non-domestic buildings such as hospitals, offices, hotels and retail; this increases to 80% when including domestic hot water (DHW) generation (Pérez-Lombard et al., 2008). In large commercial buildings such as hospitals, offices and higher education establishments, HVAC systems always represent the largest primary energy end-use (Grondzik, 2007). The energy performance of buildings can be hard to predict as it is influenced by factors such as ambient weather conditions, the building structure and envelope characteristics, the operation and control of building service systems, occupancy levels and occupant behaviour (Zhao and Magoulès, 2012). Understanding design margins is important for the replacement and design of building service systems because it provides resilience without the added cost of overdesign.

Energy demand has increased over recent years as indoor comfort was recognised as an important factor for the health, wellbeing, morality, work efficiency and contentment of building inhabitants (Shaikh et al., 2013). As energy consumption and carbon dioxide emissions have become issues of great societal concern, addressing the issue of overdesign in building services has become an important topic of research. When building service plants are replaced at the end of their useful operational life, new plants are often specified on a like-for-like basis without any due consideration. The aim of the paper is to analyse practical barriers that impact on overdesign of hospital building service systems, to illustrate the multitude of issues that can affect the issue of sizing.

2 LITERATURE REVIEW

Oversizing is common in energy infrastructure and building services systems across all building sectors, with significant additions of cost for the client and reduced performance (Djunaedy et al., 2011; Abhang, 2020). Very often, older building service systems are oversized for current needs, as they were designed to meet legacy demand of policy requirements, that have subsequently changed over time. For example, a building ventilation plant designed in the 1990's was sized to provide adequate dilution of tobacco smoke, which is no longer a concern since the smoking ban within buildings in 2007 (Geens et al., 2011). Designs must be based on accurate calculations of the requirements to assure correctly sized equipment with optimal performance (Abhang, 2020). Hospitals need to be resilient and handle crisis events. This leads to a bias towards over-capacity design of energy and building services infrastructure in order to mitigate risk (de Neufville et al., 2004; Djunaedy et al., 2011).

2.1 Establishing requirements for building services

Requirements are the basis of all engineering projects, they define what the final product or system must achieve in order to fulfil the needs of customers. Requirements, therefore, form the basis of project tasks such as planning, risk management and change control (Hull et al., 2005). Requirements are the fundamental elements of the briefing process as well as the whole project development process (Yu and Chan, 2010). The Construction Industry Board (CIB) describes the briefing process within construction as "the process through which a client informs others of its needs, aspirations and desires for a project" (CIB, 1997). A definition of a requirement provided by the Institute of Electrical and Electronics Engineers, is "a condition or capability that must be met or possessed by a system or system component

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to satisfy a contract, standard, specification, or other formally imposed documents" (IEEE, 1990). Ideally requirements should be unambiguous, complete, concise, traceable, feasible, consistent and necessary (Zielczynski, 2008). There is also a consensus amongst certain researchers that the management of requirements within the construction industry requires transparency, good communications amidst stakeholders, the innovative use of IT to capture requirements and inform decision making; many of which are currently inadequate (Chan et al., 2005; Hull et al., 2005; Chan et al., 2007). More specific concerns associated with requirements engineering include problems in defining the system scope, problems with lack of understanding among different project stakeholders, and problems in dealing with the unpredictable nature of requirements. These problems in requirement elicitation can lead to poor specifications (Christel and Kang, 1992; Hull et al., 2005). Overspecification of a requirement, also known as over-requirement, occurs within projects when the customer or designer specify a product or service beyond the actual needs of the customer (Ronen and Pass, 2008). Research undertaken by Jones and Eckert have found this to be a significant problem within building services design leading to inefficient, oversized heating and cooling systems (Jones and Eckert, 2019; 2020). Even though the systems are mechanical systems, they do not follow the rigorous requirement processes you would expect in software or engineering companies, predominately due to the bespoke nature of building service design that differs from building to building.

2.2 Risk and resilience

Due to the risk adverse culture of NHS hospitals and the need for resilience, redundancy factors are added to building service system designs, further adding to the overdesign problem. The concept of redundancy relates to the provision of additional capacity in a system so that system performance is maintained despite partial system failure (Chen & Crilly, 2014), thereby an important means of achieving reliability. They point out that redundancy definitions fundamentally fall into two categories: duplication, where an additional system of the same specification is provided (often referred to N+1 or 'like for like') and substitution, where a different solution principle is used. Oehmen and Kwakkel (2021) present other established methods addressing risk management in their engineering systems handbook. The management of margins, as a means to handle risk, also needs to be seen in the wider context of resilience on two related levels. Firstly, the ability of the building to function within specified parameters; therefore, resilience is provided by maintaining specific operating conditions. Where the system is impacted by some form of previously envisaged disturbance, the system's resilience is measured by its speed and ability to return to its original state (Dieter, 1989). Such systems may fail catastrophically under unforeseen circumstances (Weick et al., 1999). Secondly, the resilience of the overall system to maintain its core functions, i.e., in the case of hospitals to provide adequate medical care. Resilient systems may include multiple approaches to service provision, such as generators using different fuels; redundancy or spare capacity; and the use of experienced, trained management, empowered to act competently in an emergency.

2.3 Design margins

The overdesign of building service systems due to the over application of design margins is not a new phenomenon. This concern was initially highlighted in a CIBSE research report published in 1998 stating that design margins are often added by multiple stakeholders throughout the design process, very often through habit, custom and practice as precautionary measures against perceived risks without any real thought of the consequences of 'oversizing'. Whilst researchers have acknowledged that buildings, building services or other technical system are overdesigned, less effort has been placed in identifying by how much, i.e. what the margins on these systems should be. Margins is an overarching term that is used to describe the multiple contingencies added to the design or the design requirement during the design process to provide flexibility, resilience and safety (Eckert and Isaksson, 2017). Different terms, such as safety factor, excess or buffer are used to denote different purposes for the element of a design that exceeds the functional requirements (Eckert et al., 2013). Margins are added by different stakeholders for a variety of reasons across the different phases of a building services project, and whilst various industry design guides state the range of margins for consideration (CIBSE, 1998; 2012), it is left to the design engineer to decide the size and scope of margins, to apply. This practice can often lead to significant overdesign, as a margin is added for each risk rather than an aggregate margin for all risks. The cumulative impact of multiple margins coupled with poor requirements management therefore presents a challenging issue from an empirical design perspective.

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3 RESEARCH METHODOLOGY

The issue of overdesign in buildings services from a practical perspective needs to be studied using multiple research methods and approaches. The research of this paper therefore utilised a mixed methods approach. Two hospital case studies were conducted via semi-structed interviews and document analysis looking at the scope and causes of building services overdesign, from which some of the practical barriers associated with overdesign were identified. The case studies were undertaken across two acute hospital Trust sites: the Royal Stoke University Hospital (RSUH) and the John Radcliffe Hospital (JRH) in Oxfordshire. During the research interviews, open-ended questions had been developed to maximise the potential for participant response and rich data. It was necessary to adjust questions during the process, when for example, different participants raised similar issues that had not been accounted for in the original question set; hence the reflective cycle of action research facilitates the adjustment of interview questions throughout the process (see Koshy et al., 2010). Five interviews were undertaken at the RSUH between February and September 2015 whereby an oversized boiler design was studied. Seven interviews relative to a second oversized building service system, a centralised chilled water system, was conducted at the JRH between February and June 2019; this study was funded by the Centre for Digital Built Britain (CDBB). Interviews across both case studies were undertaken with a range of decision makers and project engineers involved in the boiler and chiller system designs. All interviews were recorded via a Philips voice tracer device, after which all audio files were transcribed into a Microsoft Word document and analysed following a thematic analysis approach, to ascertain the key factors leading to oversized systems. Further detail relating to the interview questions asked, and the document analysis undertaken are provided within the first authors PhD thesis (Jones, 2022).

In order to gain a rich picture of the barriers associated with building services design practice, insights from research workshops with hospital energy managers were also obtained. Whilst gaining an understanding of the barriers to energy efficiency was the key aim of the research workshops, some of the more general barriers impacting on project specifications, management and design, were also identified. The two research workshops were undertaken at the NHS, Eastwood Park Training Centre on the evenings of 21st November 2017 and 13th March 2018. A total of 7 delegates attended each of the two courses from various UK NHS hospitals. A classification of six barrier groups based on the literature presented by Schleich and Gruber (2008) and Gupta et al. (2017) was presented to the participants: policy requirements, governance and organisational constraints, data and reporting, people, economic, technical and buildings. The groups of delegates were asked to mark-up "post-it" labels with their thoughts on the various barriers to effective energy management, and to place these labels under the six category headings. The workshops provided some useful insights into some of the general barriers impacting on the development of project specifications and optimal sizing and design, as well as some of the wider constraints impacting on building service projects within hospital organisations.

Due to a lack of clarity and documentation regarding the boiler design and sizing rationale at the RSUH, an experienced building services design consultant was interviewed to reconstruct how the application of design margins plays out in practice during a typical boiler design and sizing process. This exercise provided a useful account from a Design Consultant's viewpoint of the various considerations, decision logic and trade-offs that are necessary during a typical boiler design, and provided useful learning as to the many practical barriers that are associated with building service design.

4 EMPIRICAL BARRIERS IMPACTING ON BUILDING SERVICES DESIGN

Barriers apply through the entire lifecycle of the building service system. When summarising the understanding derived from the hospital case studies and other experience, it was considered important to establish the types of barriers that potentially impact on the planning design phase and construction phase of a building services project. To ascertain these barriers, it was first necessary to understand the various project considerations that come into play during the planning design phase, and the impact factors associated with the construction phase.

The research findings of sections 4.1 and 4.2 come from the RSUH and JRH case studies, insights from the research workshops with energy managers, reflections of discussions with the design consultant, the understanding of relevant building services literature and the experience of the paper authors. From this, various project considerations and impact factors affecting each of the project planning, design and construction phases were identified. Factors listed are not intended to be an exhaustive list but to capture

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the main elements arising from the research of this paper. All project considerations and impact factors were then mapped against 'potential' and 'actual' barriers. Potential barriers are those categorised as 'general' as these can apply to all hospitals, whereas 'actual' barriers are those extracted from the RSUH and JRH case studies. For example, a general barrier associated with 'policy' requirements during the planning and design phase (see Figure 1) is local planning policy. This was raised as a significant barrier by various participants during the research workshops. Government policy requires an excellent BREEAM rating for all new healthcare buildings to gain planning consent, which is not always possible due to a controversial point system. Another general barrier that is specifically relevant to a case study of this paper, is Government 'policy' which requires outline and full business case approvals. This requirement can result in significant disruption to the planning stages of a project, sometimes up to 10 years as was noted during the RSUH case study. It is important to note that barriers identified within the case studies are not necessarily unique to that case but may also be applicable to other hospital Trusts. The method and reasoning described has been applied to each of the project considerations and impact factors, detailed within Figures 1 and 2 of sections 4.1 and 4.2. respectively.

4.1 Planning and design phase barriers

The planning and design phase consists of many elements that need to be considered during this early stage of project development. With each of these, come a range of barriers that can potentially impact on project progress and performance. Figure 1 illustrates the various considerations and related barriers.

Project Considerations	General Project Barriers	Barriers relevant to case studies
Policy	• National – setting of building regulations (Part L), but no mention of design margins or sizing rationale. • Local – Planning Policy (i.e. BREEAM)	• RSUH - Government funding policy forcing the use of PFI arrangements for new hospital buildings. • No specific regulation or guidance for building services sizing. • Government requirements for outline and full business case approvals.
Major stakeholders	• Requirements assessment prior to design. • The availability of specialist construction contractors heavily restricted due to labour and skills shortage.	• RSUH - Improper capacity requirements stated. • Risk adverse Trust agreed to PFI requests for additional capacity. • Framework provider undertaking M&V for 'guaranteed' savings.
Selection and appointment of planning and design actors	• Lack of available expertise in construction industry due to skills shortage. • Architects & building service engineers in short supply resulting in limited partner choices.	• RSUH - Designers selected by the 'SPV' are bias towards best outcomes of PFI. • JRH - Trust urged centrally to use CEF procurement framework resulting in limited choice of potential contractors.
Conceptual design	• The use of 'rules of thumb' estimates. • Excess use of design margins. • Cautious approach to design.	• RSUH - Initial design capacity requirements upheld resulting in oversized boiler system. • JRH - Initial design calculations indicated a reduced capacity requirement compared to Trust project specification.
Planning consent	• Regional – Regional Plans, Merton Rule • Local – Planning policy and applications Requirement to meet BREEAM 'Excellent'.	• RSUH /JRH - No known impacts.
Design Specification	• Lack of funds for detailed feasibility studies. • Cautious approach to design leading to excessive safety and engineering margins. • Use of 'rule of thumb' estimates. • Uncertainty around future requirements due to poor data and information.	• RSUH - Specification provided by PFI design team for thermal requirements of new hospital based on worst case scenario and 'rule of thumb' estimates. • JRH - No knowledge of rationale behind development of Trust specification.
Life-cycle analysis	• Life cycle analysis often not undertaken for building service projects.	• RSUH / JRH - No evidence of any life cycle analysis being undertaken. Large oversized equipment impacting on costs throughout life cycle.
Installer's selection and expertise	• Installers margins & competency of procurement allowing insufficient lead -time.	• RSUH / JRH - Unaware of the details from information presented, however, likely to have applied the 'next size up' approach to both project designs due to limited equipment capacity ranges from manufacturers.
Financial options appraisal	• Value engineering (first wave) • Limited appraisal of all available design and equipment options.	• RSUH - No visibility of PFI financial options appraisal. • JRH - Financial options appraisal undertaken showing poor ROI for chillers, despite this, Trust still went ahead with chiller upgrade project.

Figure 1. Planning and design phase impact factors and associated barriers

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4.2 Construction phase barriers

The construction phase of a building service project includes various factors that could impact on project installation. Figure 2 provides a list of these factors and associated barriers.

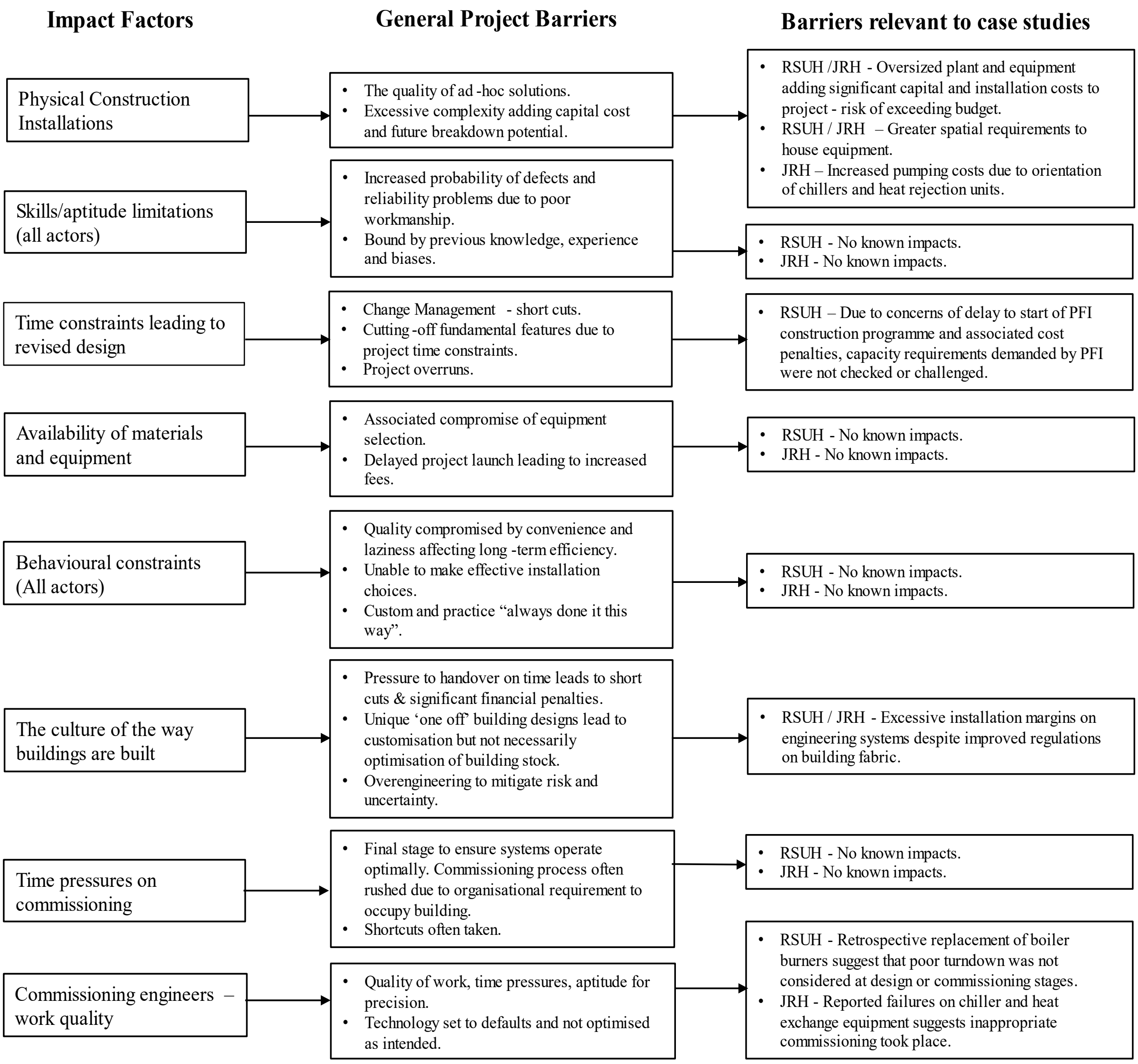

Figure 2. Construction phase impact factors and associated barriers

4.3 Insufficient communication as a major barrier

A lack of process co-ordination contributes to the excessive application of margins as there is currently no formal detailed mapping of building services design processes. In this research it become evident that numerous design groups and stakeholders are involved in a building service project across various distinct phases, starting from the development of a client brief through to project commissioning and finally operation and use. Whist the design process stages tend to follow a specific linear sequence (Jones et al., 2019) it is not guaranteed that all project related information, such as the scope and rationale for margins applied is shared with everyone in downstream phases, nor that if shared, such assumptions are challenged via upstream communication. For example, a design engineer responsible for calculating the building heating load requirement, may not be explicit about assumptions made to those responsible for selecting the boiler profile and capacity in later phases; similarly, assumptions made when specifying the boiler capacity may then not be passed onto the boiler installers. Hence, choices made during one stage are not necessarily questioned or challenged when passed to the next stage; stakeholders accept decisions that have been made before them and move on. Individual stakeholders or design groups are each making decisions relative to their function and requirements and tend to work in isolation, and hence have no visibility over the design process as

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a whole. Due to the relative flow of work between the design, installation and commissioning groups, there is no ability to challenge the scope of margins applied, once these have been introduced by each group and the design/installation has moved to the next stage. In essence, each group works to meet its own requirements without any thought as to what has been applied previously.

4.4 Barriers and their relationships

Figure 3 summarises the various barriers that have an influence and impact on building services overdesign which have been established from different data and information sources gathered from the RSUH and JRH case studies, the design consultant interview and the two research 'barrier' workshops. To provide continuity, the main barrier categories are those used during the participant workshops outlines in the methodology Section 3 and illustrated by blue rounded rectangles. Connected to each of the six main categories are individual barriers impacting on building services overdesign.

Figure 3. Summary of the various barriers impacting on building services overdesign

Whilst Figure 3 provides a detailed illustration of the many influences on overdesign, it does not show the interrelationships between these barriers which are highly interrelated. Overdesign and energy management are closely related, in that, overdesign is the cause of many energy management issues, and vice versa (e.g. inadequate data resulting from poor energy management impacts on design and oversizing; oversizing then impacts on energy performance effecting energy management); both factors, are then impacted by common organisational barriers. This complex relationship can be further extended to general barriers that are common across the whole of the NHS, and specific barriers that belong to particular Trusts, in certain contexts. A simple representation of these complex relationships is shown in Figure 4. As with the preceding figures of this paper, multiple data and information sources have been used in the development of Figure 4, the predominant source of information being that of the two hospital case studies.

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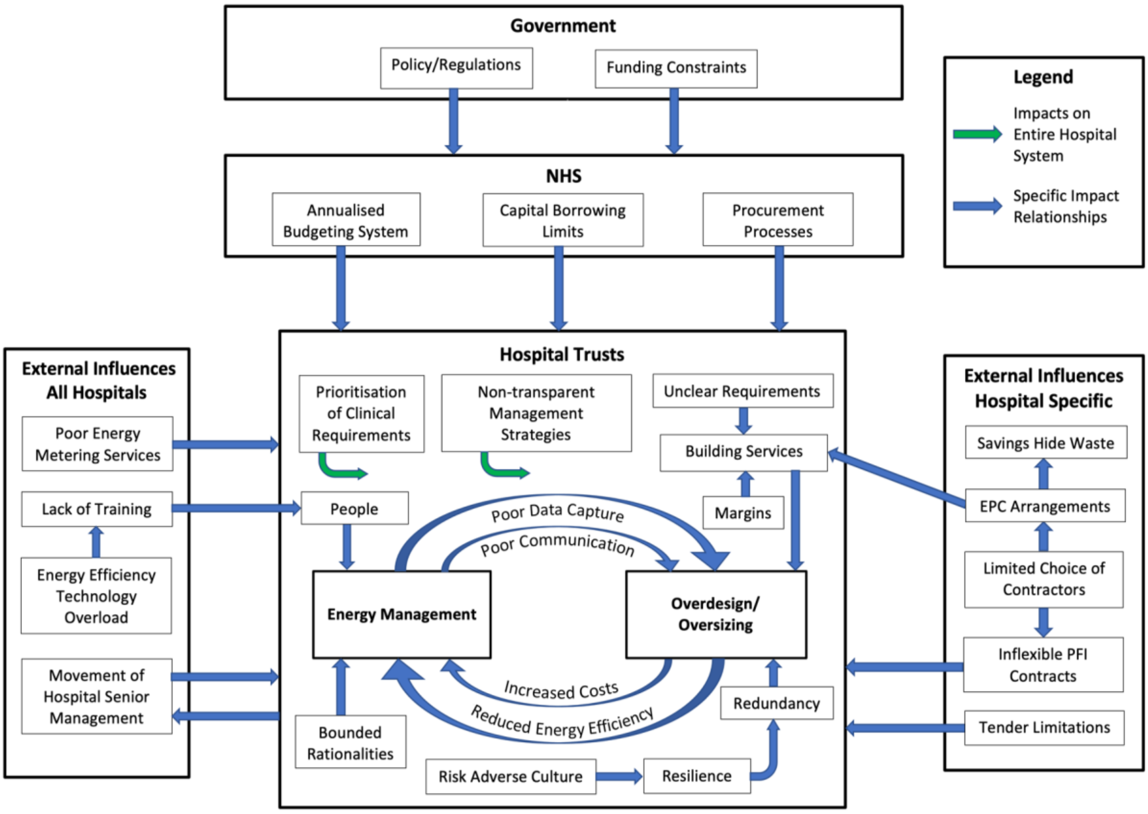

Figure 4. Relationship between overdesign, energy management and external influences

Figure 4 illustrates key barriers. Policy and funding constraints are placed on the NHS by Government, these constraints are then placed on individual hospital Trusts. Many barrier interrelations occur within hospital Trusts. General prioritisation of clinical measures and non-transparent management strategies have a detrimental impact on energy management, both in terms of funding availability and lack of prioritisation. This also impacts on building services infrastructure investment. Another major barrier specifically related to building service projects is unclear requirements. This strongly relates to poor data availability which in turn leads to the inclusion of margins. Due to the risk adverse culture of the NHS and the need for resilience, redundancy factors are also added to building service system designs, further adding to the overdesign problem. The figure also looks at external influences. Major hospital specific influences include contractual relationships. Private Finance Initiative (PFI) and Energy Performance Contract (EPC) arrangements provide powerful partner relationships. Barriers between external private organisations and hospital Trusts as contract arrangements are always heavily restricted and often in favour of the more astute private sector organisations.

EPC Partners specifically, need to be selected from a limited choice of contractors, this can be further limited by the procurement 'tender' process. The interview with the JRH case study Director disclosed the Trusts option of just two main contractors. EPC contracts together with capital funding limits can lead to a situation where the hospital Trusts maximise from the benefit of a 'one time' funding opportunity as was the case at the JRH where it became apparent that savings achieved through the purchase of new equipment, hid the issue of oversized plant. External barriers that affect all hospitals include those associated with people. Poor quality data on which to make sound decisions and a lack of knowledge and experience of the overwhelming barrage of low carbon technologies entering the marketplace results in a situation whereby 'bounded rationality' impacts on the ability to make effective decisions. This scenario is further impacted by the movement of senior estates personnel, to and from, the private sector largely a result of pay inequality, when compared to the public sector.

5 DISCUSSION

There are a multitude of barriers that impact on the oversizing issue during the planning, design and construction of a building services project. Organisational constraints within the NHS are numerous. NHS culture with annualised budgeting prevents long term planning of building services infrastructure.

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Organisational priorities are another significant barrier, favouring medical needs over building infrastructure improvements when considering the allocation of limited capital funding. This has serious implications on building infrastructure improvements, often leading to the 'last minute' opportunistic procurement of building services, to replace old inefficient equipment when funds do become available. The sporadic nature of capital funding for building services replacement often leads to sub-optimum design and sizing, partly due to NHS funding mechanisms that often require tight deadlines for design and installation. The sense of panic and urgency was shared by participants of both hospital case studies once funding has been agreed, is likely to result in the prolific use of design margins, site assumptions and design 'rules of thumb' estimates, to calculate the capacity needs and requirements of systems, both within the project specification that goes out to market, and within the detailed design.

It is evident from the research findings, that a lack of good quality data also presents a serious issue to effective design. From a general energy management perspective, the absence of good quality data inhibits the effective monitoring, and therefore control of energy use which inevitability impacts on a hospitals ability to determine precise energy use profiles and demand requirements. This leads to serious consequences when trying to size, or correctly specify, new or replacement building services infrastructure. The issue is largely due to insufficient energy sub-metering infrastructure, resulting from a lack of capital investment, but can also result from the incorrect analysis and interpretation of data.

This leads onto people barriers. The role of a hospital Energy or Estates Manager responsible for the performance of building services and energy management is wide ranging, and therefore requires various skills, training and experience to be effective. The wide range of skills required are rarely met by a single person; this leads to a skills and knowledge gap but also impacts on the ability of an Energy or Estates Manager to make informed decisions, across the broad range of work domains. Key barriers such as bounded rationality and cognitive bias therefore come into play as described in the literature (Schleich and Gruber, 2008; Gupta et al., 2017); these barriers also apply to building service design engineers and installers that often resort to 'rule of thumb' estimates and past experience to deduce system requirements; an issue that was emphasised during the Design Consultant interview.

In summary, hospitals have complex building services infrastructure that is often oversized; this creates a significant barrier to the energy performance of these systems and increases capital and operational costs significantly. System redundancy is a major factor, often increasing the capacity of these systems by 200 - 300% to ensure resilience in the event of breakdown, as seen in both hospital case studies. Cautious design practice using 'rule of thumb' estimates and excessive margins; an issue that is further exacerbated by poor stakeholder communications, are other factors of concern. Unclear requirements is another huge factor leading to overdesign, often a result of poor or insufficient data, and data analysis. Many of the barriers identified within this paper are by no means limited to building service systems; issues such as excess margins (Eckert et al., 2013) and the concept of redundancy (Chen and Crilly, 2014) also impact on a range of other engineering disciplines.

6 CONCLUSION

The research of this paper provides a useful insight into the many barriers and influences on building services overdesign potentially impacting on many NHS hospital organisations. Many project related barriers identified within the research also relate to the academic literature; for example, the NHS risk adverse culture requires huge redundancy systems and safety requirements as discussed by Chen and Crilly (2014) that contribute to building services overdesign. The issue of overdesign appears to be a systemic problem, whereby, no single stakeholder currently takes ownership of this important issue that inevitably leads to poor system performance and additional costs. Communication between project stakeholders is another significant barrier that inhibits the distribution of information between design groups. A key factor leading to oversizing is the excessive and uncoordinated application of design margins across the various project stages; unknown requirements and poor system specifications further add to the problem. There are many complex interrelationships associated with the building service design process in hospitals, with external stakeholders adding to the complexity. This points to the importance of effective communication between various stakeholders, but also the importance of clear contractual terms between NHS Trusts and external private sector organisations as witnessed during both hospital case studies. It is evident from the research contribution of this paper that it is important to look at opportunities to mitigate against the overdesign issue; this will require a multifaceted approach involving changes to design processes and procedures and hence should be the topic of further research.

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