



MANAGING MARGINS: OVERDESIGN IN HOSPITAL BUILDING SERVICES

D. A. Jones , C. Eckert and P. Garthwaite

The Open University, United Kingdom

 darren.a.jones@open.ac.uk

Abstract

The capacity of building services in many hospitals exceeds the requirements by significant amounts. Oversizing of building services has a direct impact on building efficiency and operational costs, ultimately impacting upon patient care, by diverting much needed funding. A key factor leading to the oversizing is the excessive and uncoordinated application of design margins across various project stages. Based on a hospital case study, this paper analyses the reasons for the overdesign of a replacement cooling system and raises the importance of managing margins activity to avoid overdesign.

Keywords: design process, decision making, energy efficiency, overdesign

1. Introduction

Overdesign of critical building service systems increases purchasing and running costs, as well as carbon emissions. Building on previous research undertaken by the authors, this paper looks at design margins and the apparent overcapacity of building services within hospitals (Jones and Eckert, 2016, 2017, 2018, 2019). Through an in-depth hospital case study, this paper analyses the overdesign of a new replacement chilled water system within a large National Health Service (NHS) teaching hospital, and the circumstances that led to this, in particular the lack of systematic management of current and future requirements. It raises the importance of margins as a hidden source of excess cost and energy consumption and proposes that the application of margins within building services, need to be managed activity. Based on the research findings, a number of mitigation factors that may help to prevent future overdesign of hospital building service systems, are set out and discussed.

The capacity of building services often exceeds the requirements by significant amounts (Peeters et al., 2008; Djunaedy et al., 2011; Bacon, 2014; Jones and Eckert, 2016). Oversizing of building services has a direct impact on building efficiency, capital expenditure, maintenance and operational costs, as well as environmental and societal impacts throughout its lifecycle. In hospitals this directly impacts upon patient care, by diverting much needed funding. A key factor leading to the oversizing is the excessive and uncoordinated application of design margins (i.e. the amount by which a parameter value exceeds its requirements) across the specification, design and installation, project stages. A prior case study (Jones and Eckert, 2018, 2019) looked at a boiler house, that was oversized by more than 400% against current requirements, backed up using multiple systems to provide redundancy in the event of component failure and had an increased annual running costs of 100,000s of pounds. Planned overcapacity during the specification stage may be considered necessary to allow for future expansion, whereas, overcapacity during the design and installation stages could be seen to provide flexibility, resilience, safety and

functionality. Overcapacity is often justified in the name of resilience. Hospitals are obliged to be resilient and maintain their core functionality, even in adverse circumstances. Apart from the obvious efficiency limitations of oversizing, whereby systems are incapable of operating at an optimum point (Peeters et al., 2008; Djunaedy et al., 2011), oversized systems also result in higher than necessary energy consumption and operating costs; this ultimately detracts funds from clinical services. This raises the question how systems come to be so oversized. Systems are often designed on a ‘like-for-like’ basis, replacing old oversized systems with more efficient but equally oversized systems, without conducting proper life cycle analysis, because the hospital feels confident that the system meets its need. Other contributing factors to oversizing include a lack of communication and transparency across the various project stakeholder groups, including NHS Trusts, private finance providers and building contractors/installers, and the reliance on ‘rule of thumb’ assumptions and imperfect building data to define initial project specifications (Bownass, 2001; Bacon, 2014). Energy Performance Contracting provides a private sector ‘funding mechanism’ branded a private finance initiative (PFI) for hospitals to procure large infrastructure systems such as new boilers, chillers (for the generation of cold water) or combined heat and power (CHP) systems (Jones et al., 2018). A number of commercial organisations operate Energy Performance Contracts (EPC’s) offering capital finance for building services infrastructure and associated guaranteed energy savings compared to the old systems they replace (Lee et al., 2015). This leads to substantial long-term financial burdens (de Neufville et al., 2004) and missed opportunities from an energy efficiency perspective.

The in-depth case study informing this paper is one such EPC project. In addition to the case study, the research involved the participation of five NHS hospital Trusts that collaborated across two workshop meetings to discuss the issue of design margins within building services and the wider issue of oversizing. Representatives of the Chartered Institute of Building Service Engineers (CIBSE) and NHS Improvement (NHSI) were also interviewed to gain both; industry, and health sector insights and the implications of the oversizing problem. The paper highlights both primary and secondary factors responsible for the chilled water system overdesign. Background literature relating to overdesign and resilience is presented in section two, the research methodology is presented in section three, and an explanation of how the system became oversized is detailed in section four. Lost rationale for the project is presented in section five. Discussion points, contributions and mitigation strategies are reflected upon in section five, and conclusions are drawn in section six.

2. Overdesign and resilience

Overdesign of a system implies that there is system excess that can be quantified by looking at system margins. A useful definition of a design margin is: “*the extent to which a parameter value exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included*” (Eckert et al., 2013). The term ‘margin’ is often used within companies in a number of industry sectors, particularly in the aerospace or ship-building industry (Stratmann, 2006). In the context of ship-building, margins and overdesign are seen as excess “*the quantity of surplus in a system once the necessities of the system are met*” and as capacity “*the ability of a system to meet future performance objectives using existing system excess*” (Tackett et al., 2014). In the context of mechanical engineering, design margins are added to provide flexibility; flexibility itself being defined as providing “*functionality, performance, and capacity*” each of which can be thought of as “*requirements*” (Banerjee and de Weck, 2004). Flexibility can help ‘future proof’ the design of a product, however, this will inevitably introduce a degree of overdesign (Ross and Hastings, 2005). Although attributes such as flexibility and future-proofing resulting from the inclusion of margins in engineering design are also relevant in building services design, margins applied in building services engineering are primarily applied to safeguard against uncertainty and risk (CIBSE, 2006); this practice, however, often leads to inefficient oversized solutions. Some of the most significant margins applied within building services design are to ensure resilience and reliability on two related levels:

- resilience is provided by maintaining specific operating conditions by assuring the building functions within specified parameters
- resilience of the overall system ensures core functions are maintained, i.e. to provide adequate medical care (Dieter, 1989).

Resilient systems may include several approaches to service provision, these can include; the operation of standby generators using different fuels, the provision of redundancy or spare capacity within building service systems, or the use of experienced, appropriately trained personnel to act competently, in the case of an emergency (Jones and Eckert, 2019). Alternative systems may also be considered to provide resilience rather than using the traditional like-for-like redundancy strategies, e.g. using localised DX refrigeration plant as backup rather than ‘doubling up’ on large centralised cooling systems (Oughton and Wilson, 2015).

2.1. Redundancy to assure operational resilience

Hospital building service systems are designed to continue to operate in the event of system failure, this sustained resilience is achieved through the implementation of redundancy design principles (International Atomic Energy Agency, 1986). Redundancy factors ensure reliability in the event of a full and partial system failure (Chen and Crilly, 2014). Having more chiller units than is necessary to meet the building maximum demand is an example of system redundancy. The degree of redundancy applied is dependent upon a building’s risk and resilience requirements, hospitals typically work on the basis of an N+1 redundancy strategy, i.e. the redundancy of a single chiller (N) is substituted by a chiller of matched capacity (+1). Typically, redundancy scenarios utilise building service systems on a like-for-like basis. The closely related concepts of segregation; which provides resilience on the basis that total system failure is less likely if its component parts are located physically away from each other, and diversity; which provides resilience on the basis that different system types are used to provide a common function, are other alternative strategies (Möller and Hansson, 2008). The application of a modular architecture, e.g. the installation of six small chillers each with an operating capacity of 100kW, rather than operating two large 300kW chillers, is likely to provide a number of operating efficiency and life-cycle cost benefits as the building cooling needs can be more closely matched to demand, across all four seasons. These benefits, however, may be counteracted by the likely increase in capital expenditure for the modular system due to the need for a greater number of components and increased installation and commissioning costs, thus posing an interesting dilemma for building owners and designers, over whether to opt for higher life-cycle operating costs or increased capital costs.

2.2. Margins leading to overdesign

One of the reasons for overdesign is the large range of margin values that are quoted within building services design guides, with very little published support on their definitive use, leaving design engineers to decide how to apply the margins, based on their previous experience (Jones et al., 2018). The little guidance that has been published tends to be through the promotion of better design consistency and standards (Race, 2007), however, it would seem from a number of building service engineering case studies (Crozier, 2000; Jones and Eckert, 2016) and the authors professional practice of 30 years working within the building services industry, that this guidance is largely being ignored and that the practice of applying excessive margins continues to be accepted. A Building Services Research and Information Association (BSRIA) guide to building services calculations states that “*margins should never be added during a calculation process without an adequate reason for doing so and with the approval of a senior engineer*” furthermore “*if any margins are used they should be clearly identified and a justification given for their use*” (BSRIA, 2007).

Other factors leading to overdesign in building services is poor communication between project stakeholders (i.e. clients, designers and installers) whereby assumptions, estimates and contingency margins applied, are not shared (Jones and Eckert, 2019), in addition, it is common practice for engineering design consultants to apply ‘precautionary margins’ to offset any potential liability or financial penalties that may be imposed on them, as a result of not meeting the necessary requirements.

It is therefore safe to assume that there are opportunities within the specification, design and installation process to carefully apply margins that lead to a robust solution, whilst avoiding overdesign.

The absence of good quality data (i.e. data relating to energy and thermal requirements) on which to base engineering designs, is another contributing factor to the oversizing issue that leads to many estimates and assumptions being made, and hence the prolific application of cumulative margins, by various stakeholders, to safeguard against any uncertainties or risks (Bacon, 2014).

3. Methodology

The research of this paper is based on a case study carried out as part of a Centre for Digital Built Britain (CDBB) funded study. It adopted a mixed methods approach that included; semi-structured interviews, document analysis, modelling of the case study engineering system including a stakeholder analysis, and participant workshops. The project included five NHS hospital organisations as collaborators who were invited to a launch workshop which provided a general introduction to design margins and how the cumulation of these might lead to the oversizing of building service systems. Each of the partners recognised the issues presented and offered suggestions for building service projects carried out within their hospital organisation, that could be studied. The particular hospital selected for the case study, was a high-profile case well known in NHS hospital circles as a successful PFI and EPC project; however, the Estates Director felt that while making remarkable savings compared to its 1980s predecessor, the system was seriously oversized.

3.1. The approach to the hospital case study

The hospital case study included semi-structured interviews with a range of decision-makers, designers and project managers involved in both phases of the CHP, boiler and chiller replacement EPC works. Interviews in respect to this project took place between 15th February 2019 and 10th May 2019. The researchers developed a set of questions before each interview, but ran the interviews as freely flowing conversations to allow the interviewees to explain their role and influences within the building services infrastructure design. Ensuring participants' anonymity also provided space for them to talk frankly, particularly where organisational and project constraints were perceived to negatively affect the decision-making process. Five interviews were conducted with six participants (P1 to P6) who were either currently running the hospital, or had been involved at the time of procurement.

Two further, related interviews were organised with experts outside the immediate project. P7 to provide a wider view of the oversizing issue within the building services industry and how best to mitigate against this. P8 thought to gain an NHS overview of the problem and how best to provide NHS managers with the necessary tools to ensure that oversizing of plant and equipment doesn't impact on hospital energy performance and costs, going forward. All interviews were conducted face-to-face by the first author and at least one other author; notes were also taken, capturing the salient points discussed. The interviews provided some useful detail regarding the EPC infrastructure project, highlighting key stakeholders, capital and funding challenges, design influences and processes, limitations in energy data, project constraints and subsequent operation and performance of the building service systems installed. All interviews were recorded, transcribed and analysed following a thematic analysis approach. A list of interviewees are provided in chronological order in Table 1.

Table 1. List of interviewees, in chronological order

Interview no.	Name and Job Title	Date	Duration	Interviewer
P1	Estates Operational Manager	15/02/2019	94 minutes	DJ, CE, PG
P2 + P3	Senior Operational Estates Manager and Director of Estates and Facilities	15/02/2019	68 minutes	DJ, CE, PG
P4	Technical Director - Contracting Company	05/04/2019	69 minutes	DJ, CE, PG
P5	Director of Estates & Facilities (at the project funding and initiation stage)	02/05/2019	81 minutes	DJ, CE, PG
P6	Regional Director - EPC Main Contractor	10/05/2019	64 minutes	DJ, CE, PG
P7	Head of CIBSE Certification	22/05/2019	41 minutes	DJ, CE, PG
P8	NHSI National Sustainability Lead	04/06/2019	58 minutes	DJ, CE

In addition to the research interviews, a project document review was also undertaken. The focus of the document review was to determine information such as; the project specification, project timelines, design considerations, decision processes and the funding options considered; system performance post installation and installed capacities were also explored. Six key documents were reviewed which

included; site plans and mechanical service drawings, cost information, project scope and technical specifications and post installation operational performance data. The review was carried out using key 'word' searches relative to the areas of interest via a programme toolbar, within a pdf reader.

Based on information derived from the interviews and the document review, the authors were able to model the project stakeholders, their roles and influences. In addition, a detailed engineering systems model was developed illustrating the previous system installation alongside the new project installation. Engineering calculations were undertaken based on this model to establish the current system performance relative to the previous system. The outcomes of the study were presented back to the project representatives and other NHS research participants.

4. How the system became oversized

The reasons for the overdesign in the system fall into two major categories: the way in which funding can be procured for capital expenditure projects biases hospital management towards building large systems, when they have the opportunity; and the design decisions taken in a specific project based on unclear demand, which will be discussed in the following section. The paper argues the need for hospital organisations to fully examine the needs, costs and procurement options of capital infrastructure projects before entering into long-term EPC contracts requiring significant financial commitment, through better life-cycle cost analysis and the planning of future needs. But also, the need to improve; energy data capture and analysis, design processes, and the communications and training of project stakeholders, enabling hospital managers to make more informed decisions and reduce the probability of oversizing.

The recognition for the need to tackle hospital infrastructure issues first arose in 2010. After obtaining the necessary internal Board commitment and approvals, the hospital organisation engaged their preferred framework providers to undertake an initial feasibility study in 2012. A procurement process ran across 2013/14 with the development of a specification proforma, a call for tender, and the selection and sign-off of the preferred EPC supplier in 2015 by the hospital Board. The project finished in 2018.

4.1. Capital expenditure in the NHS

Capital expenditure, often termed CapEx (i.e. funds used by an organisation to acquire, upgrade, and maintain physical assets such as property, buildings, technology and equipment) within hospitals is currently heavily restricted due to finite resources, unpredictable Government funding mechanisms and competition alongside other public sector organisations. Even when CapEx does become available to a hospital organisation, these finances are also linked to medical equipment budgets, which are often prioritised as the organisations core business; moreover, very often hospital Estates Directors are not represented on Trust Boards, and therefore are unable to secure funding for anything other than urgent reactive works and catastrophic equipment failure, leaving the opportunity to proactively replace aged building services infrastructure; a rare exception (P3). Borrowing on the open market is also difficult for NHS hospital organisations, as this is subject to internal borrowing limits, outline and full business case approval and the need to meet NHSI and Treasury requirements, all of which can take many months and significant costs to obtain. Once borrowing is approved, an EPC can provide an attractive mechanism by which borrowed CapEx is repaid (P8). The hospital had significant historic backlog maintenance issues, mainly running on emergence maintenance and was concerned about catastrophic breakdown of the aged infrastructure, leaving the hospital with no heating or cooling. The hospital Estates Director remarked "*during that year we did have failure of the existing kit and had to bring in packaged plant; and that was at huge expense*" (P3). The hospital capitalised from the 'one-time' funding opportunity and used an EPC to provide private finance that facilitated the replacement of old, inefficient energy infrastructure such as large boiler systems and chiller replacements. It was funded through the revenue of energy savings via a 'guaranteed savings' scheme, against the performance of the old system. The works were undertaken across two distinct phases:

- Phase 1 (2016/2017) - The installation of a 4.3MWe combined heat and power unit, a waste heat combination boiler, a single absorption chiller, heating and chilled water pump systems, heating and domestic hot water (DHW) plate heat exchangers and LED lighting upgrades (to

improve the overall project 'return on investment' (ROI); the Phase 1 works also included an innovative 1.6km hospital-to-hospital energy (hot water) and power link.

- Phase 2 (2017/2018) - The installation of a further two chiller units (one electric and one absorption chiller) and a number of roof mounted heat rejection units (adiabatic radiators).

The project was scoped beyond the hospital boundaries to include the installation of district heating linkage points for future connection to neighbouring university and residential buildings, enabling a staple income stream to be generated by the hospital organisation via the trading of residual heat (P5). Despite the connection points being in place, this opportunity has yet to be realised. The total cost of the entire project was understood to be just short of £50M; the finance borrowing limit over which requires UK Treasury approval.

When appraising the costs of the chiller overdesign from data provided, the CHP and absorption chiller combination relative to the Phase 1 works reduced chilled water generation costs from £70k to £14 P.A., providing a good financial outcome compared to the original system. Installation of the Phase 2 chillers, however, only reduced chilled water generation costs by a further £8k to £6k P.A. When considering the Phase 2 capital expenditure of £2.6m, it is clear that the Phase 2 project did not provide a good return on investment. The research findings, however, revealed that nobody within the hospital organisation had a full overview or understanding of the project economics and ROI. Preliminary calculations suggest that alternative systems may have provided overall 'greater value for money'.

Poor baseline data can also have a negative impact on EPC shared savings schemes due to the hospital organisation choosing to 'err on the side of caution' with regard to the client specification and hence over-estimate base-line energy demand figures to ensure equipment installed via the EPC, is not undersized (P6). NHS hospitals have notoriously poor energy and thermal metering infrastructure; data relating to hospital service flow temperatures and space and environmental conditions are also, very often, not available (P4 and P6). The absence of reliable data upon which to appropriately size building services plant and equipment results in uncertainties that lead to the use of 'rules of thumb' estimates and sizing tools on which to base site thermal capacity requirements of boiler and chiller plant. Even when reliable data is available, due to a skills shortage, attracting energy managers skilled in data analysis and energy forecasting is difficult, leaving the data under-utilised (P8). Unfortunately, because the same client specification is used to set shared savings targets, there is a potential issue whereby savings claimed by the EPC provider may be greater than the actual savings realised.

5. The lost rationale

The case study of this paper specifically focuses on Phase 2 of the EPC works; the installation of supplementary chiller plant and associated adiabatic heat rejection units. The system has multiple chillers using different solution principles. Prior to the upgrade works, there were no meters measuring the energy input or energy output to/from the hospital chillers, therefore it was not possible to definitively state the chilled water demand (P6).

The hospital organisation requirements specification requested that the chilled water upgrade works provide for an N+1 chilled water supply capacity of 2.5MW; this brief was the basis of designing the chiller upgrade which informed the 'Phase 2' works. Calculations and observations undertaken by the EPC main contractor suggest a summer (peak) cooling demand of 900kW was appropriate. An uplift of 20% was applied to offset errors in the calculation methodology increasing the summer chilled water demand to 1,080kW (circa 1MW), hence, the new Phase 1 absorption chiller rated at 1.16MW capacity, was of sufficient duty to meet the chilling requirement of the site. The discrepancy between the specification (brief) and calculated cooling requirement was brought to the attention of the hospital organisation for review, however, a decision was made by hospital managers to stay with the 2.5MW specification. As a result, the Phase 2 chiller project increased the installed chilled water capacity by a further 2.6MW (1 x 1MW absorption chiller + 1 x 1.6MW electric chiller), providing total chilled water generation capacity of 3.76MW; a system that is 276% over and above the calculated peak capacity of the site. In addition, seven x 1MW packaged heat rejection units were installed as part of the 'Phase 2' works, a heat rejection capability of 600% over and above the anticipated heat rejection needs of the site. Secondary chilled water systems, such as pumps, valves and pipework are required to accommodate the maximum load capability of the main chiller plant, consequently the margins of overdesign on the secondary systems can also be

considerable. Figure 1 provides a model overview of the original hospital systems installed in the 1980's alongside Phase 1 (in green) and Phase 2 (in blue) systems; original systems removed are also illustrated.



Figure 1. Modelling of the original and current hospital installations

Whilst the heating system components of the Phase 1 works (i.e. CHP, combi boiler and heat/power link) are illustrated along with the original standby steam boilers, these are included for completeness only to provide a full overview of the hospital systems. The components of the Phase 2 works (i.e. chiller No.1 and chiller No.3, circulation pumps and heat rejection radiators) and the absorption chiller No.2 of Phase 1, were the main focus of the study. Blue directional lines illustrate flow and return chilled water distribution, whilst the red directional lines represent flow and return heat rejection pipework.

The project has resolved significant backlog maintenance issues for the hospital organisation and overall, due to the Phase 1 works only, delivers considerable energy savings so that the obvious overdesign issue of the Phase 2 chiller system has been overlooked. Current employees of the hospital organisation were not aware of the rationale behind the Phase 2 specification that was sent out to tender. Nor were they aware of the design rationale for the project, and this became apparent when the commissioning Estates Director who had left the hospital organisation several years before completion of the new systems, was interviewed (P5). Whilst the system capacity was considered at the outset of the design, it appeared that as long as the new system continued to produce significant savings, the considerable oversizing was not questioned. This is particularly worrying considering the urgent need to reduce CO₂ emissions, and cut costs within NHS hospitals.

The project was implemented and run by three groups of stakeholders; see Figure 2. The Contracting Company has an overseeing role of the Main EPC Contractor. They interact with the hospital through monthly project meetings. The organisations had a range of participating project stakeholders, ranging from hospital managers and contracted technical personnel, through to local residents. The hospital organisation has been subjected to a significant turnover of personnel, in particular, senior management. This led to a lack of visibility across the hierarchy of the organisation and a loss of rationale for basic decisions made. Assumptions applied to the Phase 2 design specification, relating to data supporting hospital capacity requirements, target use, future growth predictions and future energy demands have inevitably been lost over time, as key personnel have left the organisation. It would also appear that the scope and ambition of opportunities envisaged at project design stage, such as an extension of the current

heat network; interconnecting university buildings and local residences, have been forgotten. Hence, the EPC main contractor and the contracting company have been instrumental in maintaining continuity of the project. However, they are not party to strategic planning at the hospital.

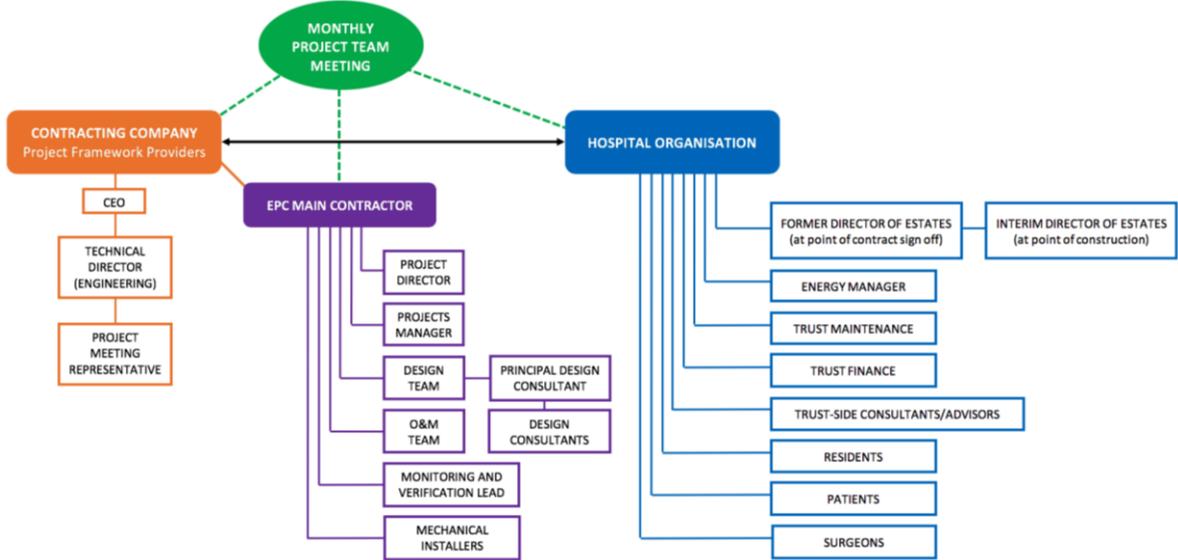


Figure 2. Scope of project stakeholders

The stakeholders’ motivation for the project varies significantly. For the hospital organisation it reduces backlog maintenance “*the funding scheme enabled me to radically change what was a completely broken infrastructure*” (P5), provides ease of maintenance (delivered via the EPC contract) “*Effectively, these schemes are really about risk management, passing the risk over to the contractor as much as possible*” (P5), improves resilience, supports growth of site energy demands, and saves money through the EPC. For the EPC provider and the contracting company the project brings a long term contract, good reputation and publicity, and a share in energy savings.

6. Discussion

Replacement of building services equipment in a hospital environment competes with medical equipment, in the same budget, and therefore its purchase is often deferred or abandoned. Adding to this, Estates Directors are not generally represented on hospital Boards, so it can be difficult to gain capital funding. It can also be challenging for hospital organisations to borrow on the open market, so privately financed EPC schemes are an attractive solution; this however presents a bias towards ‘one-time’ large projects, rather than incremental system updates, as the need arises. NHS hospitals must therefore consider the long term financial commitment that large EPC contracts require.

One of the key findings of the study identifies that, to focus purely on savings as a measure of project success, can hide very significant overdesign, particularly when based on a comparison of the new system against the older exceedingly inefficient solution. Multiple solutions may have provided savings, but there was little effort to determine if the chosen design was the most appropriate for the task. When an older systems is replaced, the new system tends to inherit any degree of the oversizing of the original, and this effect can be hidden by the savings due to improved plant efficiency. Theoretically each item of equipment should be scrutinised for its need and capacity, and whether it uses too much energy. The study highlighted a lack of clear data on temperature flows, sub system energy use and environmental data; data was available for the whole hospital site and major buildings, but many sub systems were not metered, this led to the formulation of assumptions of current use, rather than using real data. A lack of forward planning for future needs particularly for plant and equipment was also apparent, cooling and heating needs for the hospital were highly uncertain, whereas scenario planning ought to be possible. Rationale for basic sizing decisions were not captured in a form retrievable by the hospital organisation due to a high turnover of personnel; poor communications and

vague documentation also added to the issue bringing into question the need for better traceability and data capture. Explanations for the system oversizing were generally attributed to the need for redundancy and resilience, this is despite the opportunity to replace like-for-like scenarios, with innovative alternative solutions.

There are a number of mitigation strategies that could be adopted to avoid overdesign in future projects; these can be considered under the four main headings of; information, design, processes and people.

Information and data is important on various levels to capture the scope and rationale of margins used, and to better understand building energy trend profiles. Improved data collection from site and a more thorough understanding of margins added by suppliers is likely to improve design outcomes; this information could be a requirement of the contract award. Monitoring the energy consumption of medical equipment and buildings through additional metering, logging equipment and energy flow profiles are therefore important measures in tackling the oversizing issue.

From a design perspective, considering a modular architecture may result in higher upfront costs, however, these systems are likely to provide beneficial whole life-cycle cost outcomes, through improved long-term operating efficiencies. Designing like-for-like replacement systems that are based on the capacities of old inefficient systems, should also be avoided. Challenging redundancy at system architecture level and considering the use of alternative systems, or systems that can provide back-up from outside the hospital system, e.g. via a heat network from a neighbouring organisation, may help to reduce standing energy losses associated with traditional N+1 systems. Avoiding cumulative margins within engineering calculations through better stakeholder communications and transparency, and using an options approach to design, i.e. plan the infrastructure for a larger system, but don't install all units, are other important considerations.

Various processes may be adopted to reduce the risk of oversizing; failure mode analysis, risk analysis, periodic sensitivity analysis, are all examples of these. Agreeing a 'set' level of overall margins to provide sufficient resilience, is another option. Processes and systems that support the optimisation of the initial design, but also the ongoing 'in use' performance of the system, should also be adopted. Mitigation through people interventions may be effective. Having a dedicated system architect to oversee the life-cycle of project from specification through to commissioning could provide a robust solution to the problem. Improving communications between project stakeholders groups is also a key requirement. Not all Estates Managers are aware of the efficiencies of their own or proposed equipment, improved training and education will ensure that personnel are better informed, enabling them to challenge design consultants, before final decisions are made.

7. Conclusions

A starting point for this project was the hypothesis that overdesign leads to energy waste. However, many of the findings from the project, in terms of a lack of understanding of the requirements and the risks, apply equally to undersized systems. The principle cause of the chiller overdesign was due to the hospital organisations output specification, where no rationale for this was obtained. To avoid similar overdesign in the future it is important to understand how margins have arisen. The case study and discussions with hospital building service experts have confirmed that overdesign of building services is a real problem, and that sizing building systems appropriately has the potential of reducing energy consumption and costs considerably. The study has revealed that hospitals are missing clear procedures to capture the current and future energy needs and to assess surplus capacity required for resilience; this makes measuring and tracking margins difficult.

The development of appropriate methods to quantitatively assess acceptable levels of overdesign necessary for resilience, together with the creation of a model to avoid overdesign resulting from cumulative margins and other contributing factors, both within, and outside the design process, are therefore important areas of further work. The immediate impact of the project lies in the awareness of overdesign that has been raised amongst the participating hospital organisations and the companies involved. The potential impact, however, goes far beyond this project to include other building types, and a transferability to other products and sectors, such as the automotive and aerospace industries. The authors believe that the case study highlights a much wider problem of great significance; the language of achieving 'savings' from projects, with regards to specified base lines, hides potential perpetual overdesign.

Acknowledgement

The research of this paper is based on a case study carried out as part of a Centre for Digital Built Britain (CDBB) funded study.

References

- Bacon, M. (2014), "Occupancy Analytics: A New Basis for Low-Energy-low-Carbon Hospital Design and Operation in the UK", *Architectural Engineering and Design Management*, Vol. 10 No. 1-2, pp. 146-163. <https://doi.org/10.1080/17452007.2013.837254>
- Banerjee, P. and de Weck, O. (2004), "Flexibility Strategy – Valuing Flexible Product Options", *Proceedings of INCOSE/ICSE conference on synergy between systems engineering and project management*, Las Vegas, Nevada.
- BSRIA (2007), *A Guide to HVAC Building Services Calculations*, 2nd ed., BSRIA, Berkshire.
- Bownass, D. (2001), *Building services Design Methodology, A Practical Guide*, SPON Press, London. <https://doi.org/10.4324/9780203478707>
- Chen, C. and Crilly, N. (2014), "Modularity, Redundancy and Degeneracy: Cross-Domain Perspectives on Key Design Principles", *8th Annual IEEE Systems Conference (SysCon)*, Ottawa, Canada, IEEE, pp. 546-553. <https://doi.org/10.1109/syscon.2014.6819309>
- Chartered Institution of Building Services Engineers. (2006), *Guide A – Environmental Design (7th edition)*, CIBSE, London. ISBN-13: 978-1-903287-66-8
- Crozier, B. (2000), *Enhancing the Performance of Oversized Plant (AG 1/2000)*, BSRIA, Berkshire.
- de Neufville, R. et al. (2004), "Uncertainty Management for Engineering Systems Planning and Design", *Engineering Systems Symposium*, March 29-31, 2004.
- Djunaedy, E. et al. (2011), "Oversizing of HVAC System: Signatures and Penalties", *Energy and Buildings*, Vol. 43 No. 2-3, pp. 468-475. <https://doi.org/10.1016/j.enbuild.2010.10.011>
- Dieter, G.E. (1989), *Mechanical metallurgy*, SI Metric Edition. McGraw-Hill.
- Eckert, C.M. et al. (2013), "Components margins through the product lifecycle", In *IFIP International Conference on Product Lifecycle Management*, Springer, Berlin, Heidelberg, pp. 39-47. https://doi.org/10.1007/978-3-642-41501-2_5
- International Atomic Energy Agency (1986), *General design safety principles for nuclear power plants: a safety guide*, International Atomic Energy Agency, Vienna.
- Jones, D.A. and Eckert, C.M. (2016), "Design Margins: Impact on Building Energy Performance", *Proceedings of the DESIGN 2016/14th International Design Conference*, The Design Society, Glasgow, pp. 1295-1304.
- Jones, D. and Eckert, C.M. (2017), "Overdesign in Building Services: The Hidden Energy Use", In: *Proceedings of the 21st International Conference on Engineering Design (ICED17)*, Vol. 1: Resource-Sensitive Design Design Research Applications and Case Studies, Design Society, Vancouver, Canada.
- Jones, D.A., Eckert, C.M. and Gericke, K. (2018), "Margins Leading to Over-capacity", *Proceedings of the DESIGN 2018/15th International Design Conference*, The Design Society, Glasgow, pp. 781-792. <https://doi.org/10.21278/idc.2018.0520>
- Jones, D.A. and Eckert, C.M. (2019), "Empowering Decision Makers to Avoid the Oversizing of Building Service Systems", in *Proceedings of the 22nd International Conference on Engineering Design (ICED19)*, Delft, The Netherlands, 5-8 August 2019. <https://doi.org/10.1017/dsi.2019.119>
- Lee et al. (2015) "Risks in Energy Performance Contracting (EPC)", *Energy and Buildings*, Vol. 92 No. 2015, pp. 116-127. <https://doi.org/10.1016/j.enbuild.2015.01.054>
- Möller, N. and Hansson S.O. (2008), "Principles of engineering safety: Risk and uncertainty reduction", *Reliability Engineering and System Safety*, Vol. 93 No. 6, pp. 776-783. <https://doi.org/10.1016/j.res.2007.03.031>
- Oughton, D. and Wilson, A. (2015), *Faber and Kell's Heating and air-conditioning of buildings*, 11th ed., Taylor and Francis Group, Oxford.
- Peeters, L. et al. (2008), "Control of Heating Systems in Residential Buildings: Current Practice", *Energy and Buildings*, Vol. 40 No. 8, pp. 1446-1455. <https://doi.org/10.1016/j.enbuild.2008.02.016>
- Race, G.L. (2007), *Design Checks for HVAC – A Quality Control Framework*, 2nd ed., BSRIA, Berkshire.
- Ross, A.M. and Hastings, D.E. (2005), "The tradespace exploration paradigm", *INCOSE International Symposium*, Vol. 15 No. 1, pp. 1706-1718. <https://doi.org/10.1002/j.2334-5837.2005.tb00783.x>
- Stratmann, J. (2006), *Engineering Management of Early Stage Warship Design, [PhD thesis]*, University of Southampton.
- Tackett, M.W., Mattson, C.A. and Ferguson, S.M. (2014), "A Model for Quantifying System Evolvability Based on Excess and Capacity", *Journal of Mechanical Design*, Vol. 136 No. 5, p. 051002. <https://doi.org/10.1115/1.4026648>