Centre for Digital Built Britain

2018/19 General Project

[**Immediate** (**I**ntegrated **M**anagement of **M**argins through **E**valuation, **D**es**I**gn, **A**nalysis, **T**racking and n**E**gotiation)]

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Abstract

Over-engineering is a hidden source of inefficiency in building service systems and can add significantly to their design, installation and running costs. Over-engineering also reduces the sustainability of systems, increasing maintenance and replacement costs and whole life CO_2 emissions. One cause of over-engineering stems from the cumulative effect of margins (error, safety etc.) added to the specification by multiple stakeholders, to mitigate against their own particular risks. The project carried out a case study of a replacement energy system at the Oxford John Redcliff hospital, a recent PFI project.

Although the new system makes considerable savings compared with the previous failing system, the system size appeared disproportionate. Individual stakeholders agreed that the new system was overdesigned, but could not quantify or cost the overdesign. Most were unaware of the rationale behind the high specification system, so that margins accumulated and could not be challenged. The case study illustrated how a rational decision at the time, lead to an oversized solution.

The project analysed the causes of the overdesign relating to procurement and specification and developed insights that can inform the decision making and management of building service projects. It also developed recommendations for designing flexible building services with suitable margins.

1. Introduction

The capacity of building services in many NHS hospitals vastly exceeds requirements. This oversizing has a direct impact on a building's efficiency, capital, maintenance and operational costs, in addition to the environmental and societal impact throughout the building's lifecycle: ultimately this 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 various project stages. The concept of a margin is used formally or informally in the engineering of complex machinery. In particular the aerospace industry has well established procedures for managing safety critical systems, they establish maximal loads through worst-case scenarios and add a standard percentage (typically 50%) as a safety factor. The system is then optimized to within a few percent above the required value, which also includes the safety factor. Individual components and the system still often carry high margins. Aerospace or other areas of complex engineering are well aware that overdesign leads to increased cost and energy use, and margins beyond 5 – 10% on major systems are rarely acceptable. Previous research suggests that excess costs associated with oversizing of energy infrastructure ranges from 10-33% (Peeters et al., 2008; Djunaedy et al., 2011).

2. Methodology

At the onset of the project, we had expected to look at multiple case studies in the five partner trusts of the project. All trusts recognized the problem of overdesign and nominated potential installations on their sides. We decided to focus on the CHP and chiller systems at the Oxford John Redcliff (OJR) hospital, as the trust was very keen and the project was very recent. The OJR solution is highly innovative: the OJR site was connected with the Churchill hospital via a limited district heating network, where underground pipes connect both sites throughout the summer months. The OJR project become a flagship project for the contractor, a specialist in district heating systems. The new system replaced a very old steam boiler of similar capacity and the cost is being recovered from savings on energy expenditure.
As part of the case study we

- Interviewed key project stakeholders in the project
  - Current and past estates directors
  - Current service manager
  - The Carbon and Energy Fund, who advise NHS trusts in building projects
  - The contractor, who designed, built and manage the project
- Interviewed experts from relevant organisation
  - Chartered Institution of Building Service Engineers (CIBSE) on installation guidelines
  - NHS Improvement (NHSI) on how procurement projects work in the NHS
  - A medical device expert on the of use of medical devices in hospitals and measurements of their energy consumption
- Undertook a review of project documentation
- Modelled the system and the energy consumption in the building (we are awaiting the release of additional data)
- Modelled alternative system designs

All interviews were recorded, transcribed and analysed following a thematic analysis approach. The results of the study were presented back to the representatives of the OJR and other trusts on the 3rd of July (the slides are appended). We are also planning a project workshop with CIBSE in the autumn to reach a wider audience.

3. Description of the system

The CHP and chilled water systems were installed across two distinct work phases. Phase 1 included the replacement of four high temperature hot water boilers (HTHW) with a 4.3MWe CHP, a combination boiler, a connecting pipeline to the Churchill Hospital and a 1.16MW absorption chiller; other downstream services such as plate heat exchangers and LED lighting upgrades formed part of the Phase 1 scope of works. The CHP generates both heat and power for use at the OJR hospital but also supplies the Churchill hospital with heat and power via a 1.6 mile underground trench.

The waste heat from the CHP is prioritised based on providing best economic value. In the first instance the waste heat serves the space heating and domestic hot water requirements of the OJR site as the primary user. Once the OJR requirement is satisfied, excess heat is then distributed via pump-sets to support the heating requirements of the Churchill site as the secondary user. If the Churchill hospital demand is satisfied, waste heat is then directed to the absorption cooling plant (i.e. 1 x 1.16MW unit + 1 x 1MW unit) as the final user before the waste energy is rejected to atmosphere, via a dry air cooler. From a sizing perspective, due to the extension of the heating distribution network to the Churchill site, the installation of a much larger CHP unit was possible, whereas prior to this initiative a much smaller 2.1MW CHP unit was considered to be the optimum size. It is understood that for the majority of the time, the hospitals power needs are largely met by the $4.3MW_e$ engine. The Jenbacher CHP unit has an exceptional turn down ratio, so that it works efficiently at different levels of loading. The exact seasonal demands on this system, however, were not clear from the data provided; it is envisaged that additional data collection will inform future thermal and power modelling of the system.

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 JRH chillers, therefore it was not possible to definitively state the chilled water demand. The Trust 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 were undertaken by the contracting design consultancy which suggested a summer cooling demand of circa 1MW was appropriate for the OJR hospital, 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 and calculated cooling requirement was brought to the attention of the Trust for review, however, a decision was made by the Trust to stay with the 2.5MW specification. As a result, the Phase 2 chiller upgrade project increased the installed chilled water capacity by a further 2.6MW (1 x 1MW absorption chiller + 1 1.6MW electric chiller), providing total chilled water generation capacity of 3.76MW; a system that is 73% over-capacity. In addition, seven x 1 MW packaged adiabatic heat rejection units were also installed as part of the ‘Phase 2’ works, a heat reject capacity 7 times over capacity.

If we think of margins as ‘system capability minus the max requirement’, the above chiller installation can be represented by the formula:

$$\text{Margins} = \text{Capability} - \text{Max Requirement}$$
$$\therefore\ 3.76MW - 1MW = 2.76MW \text{ of margin allowance}$$

i.e., 276% in excess of requirement.

The secondary systems, such as pumps, valves, and pipework, still need to be able to accommodate the maximum load of the main systems, consequently the margins of overdesign on the secondary systems can be considerable. The capital, operational and on-going maintenance costs of the chiller system over-capacity are significant and are subject to future modelling upon the receipt of further site data.

The project has resolved the backlog maintenance issues of the Trust and delivers considerable savings, so that the obvious overdesign issue has been overlooked. Current employees for Trust were not aware of the context behind the specification that was sent out for tender, nor were they aware of design rationale for the project. This become apparent, when we interviewed the commissioning estates director, who had left the Trust several years before completion of the new system. 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 over-sizing was not questioned. This is particularly worrying considering the urgent need to reduce CO_2 emissions, in addition to cutting costs for the NHS.

4. Reasons for the overdesign

To avoid similar overdesign in the future it is important to understand how these margins have arisen. Some of the factors are inherent in the way the NHS operates, while others apply to other building types as well. These factors will be analysed in the more detail in a paper under preparation, entitled “Margins in Building Services Design: a hidden cause of inefficiency” which will be submitted to the Journal “Energy and Buildings”. The following provides a summary of our key findings.

The NHS related factors include:

- The funding models of capital projects in the NHS: it can be difficult for Trusts to borrow on the open market, so that PFI schemes are attractive. This presents a bias towards “one-time” big projects, rather than incremental systems updates as the need arises.
- Government funding is erratic and dependent on political priorities and funding opportunities, which fosters a “grab when you can” attitude
- Replacement of building services equipment competes with medical equipment in the same budget, and its purchase is often deferred or abandoned
- Guidelines from NHS are frequently treated as “rules” rather than recommendations
- Estates Directors are not generally represented on Trust Boards or may not have voting rights, so that it can be difficult to fight for capital project funding
- Fluctuation in NHS staff numbers: Trusts struggle to compete with the private sector and there is a very high turnover of engineering staff
- Trusts rely heavily on consultants and as a result, lose their “corporate memory”

Understanding current and future energy, heating and chilling needs

- Unclear scope of the project: the project was sized to accommodate potentially all buildings at the OJR, in addition to the Churchill hospital. It also was intended to provide heating for local Oxford University buildings within a district heating network, but currently this network only serves the OJR and Churchill hospitals

- Lack of clear data on temperature flows, sub system energy use and environmental data: Data may be available for the whole site and major buildings but not for sub systems
- Lack of forward planning for future needs (particularly for equipment, cooling/heating needs, hospital use): the future need is highly uncertain, but scenario planning ought to be possible

Lost/obscure rationale for major sizing and design decisions

- Assumptions of current use rather than real data used. Future growth not clear to participants
- Rationale for basic sizing decision not captured in a form retrievable by the Trust
- Consultants for the Trust, CEF and the main contractor have greater continuity and therefore greater formal and informal memory
- Explanations for the system oversizing were generally (and somewhat inaccurately) attributed to the need for resilience

Resilience is seen as an overall property of the hospital, to keep its essential services functioning. Therefore it is considered essential to have back-up or alternative systems that can maintain this functionality. However the associated risks are not always discussed in this context this context.

Industry typically has an N+1 redundancy policy, i.e. having at least one spare system. In building services larger systems often provide greater efficiency, which the result that with an N+1 back-up system, backups can be very large and expensive to run (the OJR has 7 absorption chillers).Typically, a modular system (a larger number of small units, rather than one or two large units) would allow smaller capacity redundant units in the system and allow flexibility (Ross and Hastings, 2005). The hospital's chiller system had alternative chillers based on different principles and fuels as redundancy.

In the OJR some of the initial specifications were challenged by the PFI contractor, however the system is now running and does not appear to be scrutinised periodically. The trust is happy because the system is paying for itself through savings, which have also been augmented by tariff changes.

5. Mitigation strategies

There are a number of mitigation strategies that could be adopted to avoid this type of overdesign in future projects. The potential strategies will be described in more detail in a paper entitled "Mitigation Strategies and Alternative Solutions for Building Services Over-design, which will be submitted to the journal "Building and Environment". However to address the problem more systematically considerably more research will be required.

It is possible that the previously quoted equation;

margins = capability – max requirement

may be extended to include an overall 'safety margin' that represents all project margin factors agreed from the design outset. This can be represented by the equation below, which may help to rationalise the total margins applied:

Margins = capability – max (requirements) * safety factor

The case study revealed that – unlike in the aerospace or automotive industries, many Trusts do not have a clear understanding of their current and future requirements and the risks that they are subject to. The following list, gives an indication of what remedial measures that could be taken.

- Information
  - Capturing margins wherever possible
  - Capturing rationale for margins and design decisions
  - Improve collection data from site
  - Improve understanding of margins added by suppliers. This information could be a requirement for the award of a contract
  - Understanding part-load capability of the equipment. Not all estates managers are aware of the efficiencies of their own or proposed equipment on full or part load.
  - Monitoring the energy requirement of buildings and medical equipment (where feasible)
    Additional Metering, Logging equipment, Energy flow profiles
- Design
  - Introduce modular system architecture
  - Avoid like for like replacement
  - Avoid cumulative margins
  - Challenge redundancy at system architecture level
  - Back-up supplies may be possible from outside the system
  - System optimisation: design plus use
  - Use an options approach, i.e. plan the infrastructure for a modular larger system, but don't install all units.
- Processes
  - Risk analysis
  - Failure mode analysis
  - Agree a level of overall margins to provide sufficient resilience
  - Monitoring margins throughout the design, installation and commissioning process to include changes to the system
  - Periodic sensitivity analysis
- People
  - Have dedicated system architect to oversee life-cycle
  - Improved communication between stakeholders
  - Improve training and education of staff
  - Incentivise employees to stay with the Trust

One important measure to reduce overdesign and wastage is to reduce the size of redundant systems. This could be achieved by going beyond the system boundaries of individual hospitals. For example, other local hospitals can be used to supply medical services in case of emergencies, so redundancy systems could be scaled down.

In addition hospitals could collaborate with other large users, such as a university, school or even a district heating network to provide redundancy. Many hospitals produce large amounts of excess, most of which is vented, but could potentially be used in other applications, such as providing to heat to local buildings, providing cooling (via chillers), using the hot water for leisure or other industrial processes. These systems could be configured such that they are only used if excess capacity from the hospital is available. For example the hospital could provide heating to neighbouring residential houses, with their own gas boilers to use as necessary. The OJR hospital in particular is large and is either independent of the national grid, or to a greater or lesser extent, supplies the national grid. However, the grid could also be used to provide a level of redundancy. This project did not look in detail into the requirements and capabilities of adjacent systems, however it is clear that a system of systems approach would be highly beneficial.

A clearer picture the risks that need to be mitigated would also be highly beneficial. The resilience strategies for these risks might lay beyond heating, water and energy provision. In particular it would be useful to distinguish between short term risks, such as heat waves, epidemics or terrorist attacks, which place a high demand on the hospital but can be compensated for by cancelling or postponing other services: and long term risks, such as an aging population or the effects of obesity, for which the hospital needs to be ready, but has advanced warning and make advance preparations.

One of the key findings of the project identifies that, to focus on purely 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. Several solution options 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 the same degree of the oversizing found in the original, and this effect can be obscured by the visible savings resulting from improved plant efficiency.

6. Discussion

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. There appears to be a link between undersized and oversized systems, in that hospitals may need to put in local supplementary systems, such as small chiller units which, while flexible, might be less efficient than a larger system would be.

The immediate impact of the project lies is the awareness of overdesign that has been raised amongst the participating Trusts and the companies involved. The potential impact, however goes far beyond this projects to other building types. Sizing building systems appropriately has the potential of reducing CO_2 emissions and energy costs considerably.

For Digital Built Britain this project provides a case study, of a highly complex system that shows the need for

- Monitoring the energy, water, and heating use to understand the requirements
- Modelling the current systems to understand the changing demand side, so that systems can be modified if they are not efficient, or alternatively, so other uses can found for excess energy, heat or cooling produced.
- Using simulation to understand future demands when major purchasing decisions are taken

Conclusions

The case study, and discussion with hospital building service experts have confirmed that overdesign of building services is a real problem. Due to the frequent change of personnel, the Trust lost sight of the rationale for which the margins were added. The study has revealed that hospitals are missing clear procedures to capture the current and future needs and to assess the surplus capacity required for resilience. This makes measuring and tracking margins difficult.

We 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.

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