



## **DESIGN MARGINS: IMPACTS ON BUILDING ENERGY PERFORMANCE**

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### **1. Introduction**

This paper will examine the addition of design margins for energy infrastructure throughout the design process. Energy efficiency in building and infrastructure design is necessary to deliver a low carbon future in line with the UK Climate Change Act 2008, which set trajectory targets for the reduction in net national carbon emissions “at least 80% by 2050... against a 1990 baseline” [NHS Sustainable Development Unit 2008]. It will argue that care must be used when applying margins to ensure that collective effects do not undermine the ability of systems to be energy efficient.

Design margins are added throughout the design process, for different reasons, affecting components to whole systems design. Design margins are excess capacity over and above functionality capacity, regardless of the motivation for their addition [Eckert et al. 2013]. Whilst there is significant opportunity in the design process to carefully assess margins added overall and positively affect the final outcome, there is also a need to ensure multiple margins do not have a cumulative effect, ultimately leading to an over-engineered, inefficient solution. In the case of design for energy efficiency this may negate the desired outcome; the capacity of the infrastructure is too large to allow the system to be energy efficient [Djunaedy et al. 2011], [Bacon 2014].

The research in this case study examines the energy infrastructure in a hospital, with specific focus given to the oversizing of a centralised boiler plant. The paper also highlights empirical design limitations of ventilation systems and builds upon other examples of building infrastructure oversizing [Peeters et al. 2008], [Djunaedy et al. 2011], [Bacon 2014]. Public healthcare is a challenging area for any designer to work within; multiple organisational constraints and complex delivery requirements combine to present specific problems. The research literature background in section two, lays out the reasons for consideration of design margins in relation to building and energy infrastructure. The research methodology is presented, including its limitations before the case study is detailed in sections three and four. Further examples supporting the focus of the paper are discussed in section five, before the paper draws conclusions in section six. Ultimately, more questions are posed about how to moderate information for non-technical decision-makers to better support design outcomes.

### **2. Literature and background**

The influences upon choices for new energy infrastructure in buildings are broad. Building design choices are linked to the organisation occupying the space and potentially include internal and external governance and policy, numerous strategic decision-makers and existing infrastructure design or technical specifications of components. In the case of critical infrastructure, such as emergency services provision, utilities or others required in times of crisis, there is also a need for buildings to continue

operating uninterrupted. There is a bias towards over-capacity design of energy infrastructure to mitigate risk [de Neufville et al. 2004], [Djunaedy et al. 2011]. As complex organisations, with multiple legislative and quality standards with which to adhere to, NHS hospitals require large levels of building services infrastructure to ensure continual, optimal performance [Shiell et al. 2008]. They are particularly challenging environments with infrastructure adapted for delivering medicine that involves energy intensive practices; for example, utilising radioactive substances, medical gases, infection control protocols, high-powered laser and magnetic machinery. The scale of the challenge for healthcare is therefore an interesting and demanding problem. The NHS represents 3-5% of UK carbon emissions, when including hospitals and other estate, transport impact and pharmaceuticals [Wilkinson et al. 2007]. Decisions, which are applied at all levels during the design process, in either an individual component part or whole system considerations can be grouped under the category of 'design margins'. A useful definition 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]. This paper continues saying "Most components or systems have the ability to absorb some degree of change. This arises from incorporating margins. These are added by different stakeholders for a variety of reasons" [Eckert et al. 2013]. These design margins are often defined at the beginning of project design to provide flexibility; flexibility itself being defined as providing "Functionality, Performance, and Capacity" each of which "consists of many attributes, which can also be thought of as requirements" [Banerjee and de Weck 2004]. In the case of the energy infrastructure for hospitals, design margins must deliver peak load capacity requirements. In addition, energy infrastructure must be backed-up for emergencies, such as a loss of external utilities. The majority of design margin research reviewed aimed to tease apart and categorise the various reasons why and where margins are added to a design specification, analysing which are effective and which may be problematic. Ross et al. in their 2008 paper, describes the influences that might occur for a system to require modification, "change agents", and the potential outcomes of design decision-making [Ross et al. 2008]. In earlier research papers, the need to understand and specifically design in margins, particularly when considering longevity in design, also looked at the categorisation of different approaches to the challenge [de Neufville et al. 2004], [Saleh et al. 2009].

Ensuring original fixed specifications assess future external trends is unlikely to be the responsibility of the design engineer and more probably undertaken by strategic decision-makers. This is likely to create an initial specification to financial, lifespan and Return-on-Investment (ROI) type, non-technical parameters. One paper goes so far as to say that the "analysis of markets and customer usage is neither in the engineers' job descriptions nor in their training" [de Neufville et al. 2004]. Furthermore, recent research from a user-centred design perspective, acknowledges the need "to embrace the experience of a wider body of stakeholders" and how the education and training for the design and management team must improve "to fulfil social, environmental and economic requirements" [Clements-Croome 2013]. Further research states that "engineering does not typically design for a range of possibilities. It designs to fixed criteria" [de Neufville et al. 2004]. Their paper goes on to describe how "traditional engineering typically manages risk through fixed specifications", negating the need for designers to consider "probabilistic analysis" and thereby ensuring protection "from responsibility if their structure fails" [de Neufville et al. 2004]. This idea of designing systems to fixed parameters is a common theme within research papers; "usually the range of expected behaviour is fixed in specification" [Banerjee and de Weck 2004]. Bacon also determines "that building energy performance directly relates to the engineers assumptions based upon occupancy levels, which are often standardised, leading to over-engineered systems for maximum occupancy levels" [Bacon 2014]. Further research determines "The widespread use of simple sizing tools – "previous experience" and rules-of-thumb – could be an indication of why oversizing is so prevalent" [Djunaedy et al. 2011]. In some cases "many decisions are made at detail level, with limited consideration of overall solutions and overall performance/cost ratio" [Almefelt et al. 2005].

It is an objective for some design engineers to ensure that the systems, particularly long-lived, complex systems, contain elements to enable an ability to absorb change or be altered easily for the future. This can mean different things; for example, the ability to respond to, or maintain functionality in a changing external environment, an ability to be upgraded, optimised or increase longevity. Decisions are made

throughout the design process considering how products will act in future; this can include their compatibility with other technologies, how easily future changes can be applied all within a potential framework of investment decision-making, such as ROI [Saleh et al. 2009]. This is balanced by a need to ensure the design is correct for now, ensuring products are competitive and resource efficient, fitting within limited specifications. Banerjee and de Weck explore the conditions upon which value or optimal performance can be delivered in systems engineering by applying alternative valuation methods [Banerjee and de Weck 2004]. They briefly discuss the particular needs of civil architecture to deliver ‘extensionality’ or the need for the system to be scaled up significantly if future requirements demand this, with the initial design encompassing elements to achieve such expansion [Banerjee and de Weck 2004].

Other research examines how energy efficiency is considered within the design process arguing that energy efficiency is framed within the context of cost, wider environmental or resource parameters, legal frameworks or technical or functional requirements [Albers et al. 2014]. The Climate Change Act 2008 currently provides a legal necessity to properly ensure energy infrastructure will be at the optimum conditions for efficiency. Bacon states that there is a “need for a fundamental change in... the engineering design process” [Bacon 2014]. He also cites various government and professional organisation reports suggesting a new approach to building design, utilising new innovations and techniques, is needed to effectively deliver lower energy consuming buildings [Bacon 2014]. Part of this reduction in energy use will be managed within the existing building stock using data driven techniques, such as Building Management Systems (BMS), currently utilised in many NHS Trusts [Jones 2014]. However, the management of energy systems within hospitals alone will not provide sufficient delivery to enable the challenging carbon emission targets required by the Climate Change Act 2008 [Bacon 2014]. It is likely, given the current economic position of the NHS, that much of the building stock will require on-going upgrading and improvement, involving significant design engineering input. Bacon’s research is echoed in some design margin paper findings, albeit he approaches this from a different angle, arguing that “conventional design practice grossly over-estimates occupancy”, which therefore adds significant energy load to a building [Bacon 2014]. This oversight has been flagged previously in a paper which states “uncertainty and inefficiency in systems’ operation and use can readily develop through lack of attention to detail for occupants’ requirements” [Bordass and Leaman 1997]. The heuristic approach to energy infrastructure engineering design can also lead to significant oversizing, above 25% additional capacity [Djunaedy et al. 2011]. The excess cost associated with oversizing of energy infrastructure ranges from 10-33% [Peeters et al. 2008], [Djunaedy et al. 2011]. The background literature, combined with the case study and other examples, lead the author to explore the potential conflict between designing for energy efficient infrastructure and cumulative design margins.

### **3. Research background and methodology**

The issue of hospital engineering systems overdesign within the context of this paper originated from wider PhD research looking at strategic energy management in Hospital Trusts. The broader research aims to establish how decisions are made within NHS hospitals, and how the implications of such decisions affect the energy performance of the organisation and its buildings. The research focuses on stakeholder relationships, decision processes, governance systems and barriers to efficiency, all within the specific context of energy management. The research was undertaken as semi-structured interviews with a range of decision-makers across the hierarchy of the hospital Trust, between February and September 2015. In total, eleven interviews were completed; these included staff from the hospital involved in or directly responsible for energy management, higher-level decision-makers without technical backgrounds, peripheral clinical liaison staff and an external design consultant (Table 1). All hospital staff interviews were conducted face-to-face, recorded and subsequently transcribed. The interview with the external design consultant was facilitated via a telecom call; notes were taken, capturing the salient points discussed.

Nine interviews were conducted initially, whereby general discussions regarding the hospital’s ‘strategic energy management’ practices opened up further conversations in respect to this specific case study area; the boiler house design and specification for the new PFI building contract. For clarity, the term ‘boiler house’ in the context of this paper refers to the ‘boiler system’, rather than the building envelope

in which this system is housed. The interviews provided a useful overview of the decision processes specific to the boilerhouse design, highlighting key influences over the design specification, limitations in technical knowledge and a general acceptance of the boiler over-capacity. As the boiler house example grew in significance, a further two interviews were organised; one with a Trust-side project engineer directly involved in the boilerhouse scheme [Interview - P10] and another, with an experienced building services design consultant [Interview - P11]. These interviews included general engineering conversations, such as what and how heuristic parameters are applied during a boilerhouse design process, as well as more specific conversations about the boiler example.

**Table 1. List of interviewees, in chronological order**

Interview no.	Job Title	Date	Duration	Interviewer
P1	Deputy Director for Corporate Services	12/02/2015	48 minutes	DJ, CE
P2	Head of Environmental Sustainability	12/02/2015	62 minutes	DJ, CE
P3	Estates Operation Manager	12/02/2015	63 minutes	DJ, CE
P4	Energy Manager	12/02/2015	54 minutes	DJ, CE
P5	Corporate Services Matron	12/02/2015	17 minutes	DJ, CE
P6	Divisional Finance Manager	19/03/2015	21 minutes	DJ
P7	Deputy Head of Supplies & Procurement	19/03/2015	40 minutes	DJ, CE
P8	Estates Development Manager	20/04/2015	34 minutes	DJ
P9	Clinical Board Member	31/08/2015	30 minutes	DJ
P10	Senior Project Manager	16/09/2015	20 minutes	DJ
P11	Chartered Building Services Design Engineer	28/09/2015	45 minutes	DJ

Due to the long time lapse between project completion and the research interviews, external consultants and other key people involved in the boilerhouse design were unable to be contacted for the research. Therefore, some gaps should be presumed to exist within the overall picture of the project development. In addition to the research interviews, a document review was also undertaken. In the authors capacity as an independent energy consultant to the Trust, full access to project documentation was provided. The focus of the document review was to establish what factors during the design process had led to the over sizing of the boiler plant, and what margins had been applied. A total of 567 documents were reviewed, these were understood to represent the entire project database, which included; site plans and mechanical service drawings, project correspondence, cost and budget documentation, scope of works, project plan schedules, health and safety records, minutes of project meetings, tender documents and technical specifications, all specific to the boiler house project. The review was carried out using key 'word' searches (e.g. capacity, heating load, kWh) via programme toolbars, within a pdf. reader and MS Word. A large proportion of the documents were scanned images, and so not compatible with the search function; these documents were instead, skim read. Where areas of potential interest were identified, text was studied in greater detail. Despite this thorough review, project documentation did not allow the author to specifically determine the different margins, and where these were applied during the specification and design process. From the information as a whole and the body of research that exists around design margins, it is safe to make certain hypotheses. Particularly important are where in the process design margins were applied, their cumulative effect and the lack of checks against which to benchmark these assumptions.

## **4. Case study – the Royal Stoke University hospital boiler house**

### **4.1 Overview**

Boiler house designs vary from hospital to hospital dependant on the type of engineering infrastructure installed, and the heating medium required. The most prevalent types of boiler systems used within UK hospitals are; low temperature hot water (LTHW), medium pressure hot water (MPHW) and steam. The

Royal Stoke University Hospital utilises both LTHW and steam boilers within its centralised boiler house, however because the steam generation process is predominantly used for sterilisation, the steam boilers have not been considered within the scope of this study. The focus of this paper is therefore the main LTHW boilers that generate hot water to a district-heating network supplying various buildings across the site, with space heating and domestic hot water (DHW).

The large over-specification of the boiler house at the Royal Stoke University Hospital, currently running at four times the capacity needs of the Trust, is worth examining from a design margin perspective. Previous research shows that oversizing is common in energy infrastructure, with significant additions of cost for the client [Djunaedy et al. 2011]. In particular, the case study showed problems relate to the engineering design and the Trust's inability to rectify the design, although attempts were made to modify the PFI contract. It is arguable, based on the case study boiler house design, which is supported by other studies, that the application of some design margins need to be challenged [Peeters et al. 2008], [Djunaedy et al. 2011], [Bacon 2014].

The margins that were applied in the case of the Royal Stoke boiler house design suggest a long-term view of healthcare trends were not fully considered. Even cautionary capacity assumptions should not deliver an actual capacity design at four times requirement. If we accept that the best case argument for the existing boiler design was that it was responding to an increased capacity requirement in future, we need to examine the potential reasons behind the decision; the reasoning such a margin was delivered. These reasons are difficult to predict and sometimes conflicting. The strategic direction for the NHS is for delivery of certain healthcare interventions and treatments to be provided in centres more local to the home of patients, and where possible, at the patients home [NHS England 2015]. Technology trends are also moving the provision of intensive healthcare treatments away from centralised hospitals; for example, the development of home-based renal dialysis units [NHS SDU 2015]. Both would lessen the future energy requirements for healthcare. However, there is the possibility that hospital treatment will continue to become more energy intensive as continuing advances in medical technology occur. Demographic information shows an ageing population, with potentially increasingly complex health needs and conditions that require longer-term treatments, again adding to the energy load. The impact of climate change could further increase hospital energy use, either through increased demand for winter heating and summer cooling, or by increased demand through population health risk [Lomas et al. 2012]. The health risks for the population are proposed in the UK Climate Change Risk Assessment and suggest an increased demand for NHS treatment and social care [HM Government 2012]. If retrofit options, such as those described by the DeDeRHECC project were implemented strategically across the NHS estate, the increased demand for heating and cooling could be lessened [Short et al. 2012 ], [Lomas et al. 2012].

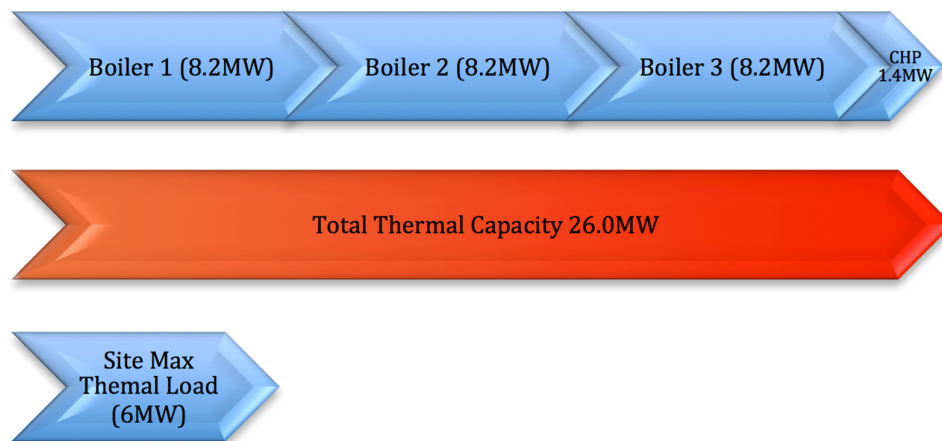
#### **4.2 Specifics to the oversizing of the Royal Stoke University hospital boilers**

Coal fired boilers were originally used to provide space heating and domestic hot water at the Royal Stoke University Hospital site, these were subsequently converted to natural gas in their old location; an area that has more recently been used to build a dedicated supplies and procurement centre. Despite conversion to gas, the 30-year old boilers were replaced during the late 1990's. Due to Trust financial constraints and the down time associated with their replacement, the Trust entered into a mini-PFI agreement with Scottish and Southern. The mini-PFI was the design and build of the energy centre, based upon requirements provided by the Trust and full PFI contractors. The new energy centre was built during 1998-99, however, because of integration and contractual issues between the Trust, the PFI and Scottish and Southern, the Trust took the decision to buy out the mini-PFI with Scottish and Southern, and take ownership of the energy centre. In order to meet the thermal requirements of the new PFI development, the energy centre then had to be upgraded, something that Trust side engineering staff didn't agree with, as it already "seemed to be rather over dimensioned, having three, 4 megawatt (MW) hot water boilers [Interview - P3].

From the detailed review of 567 boilerhouse project related documents, just a single paper entitled 'Energy Centre Report' dated 20th December 2006 was found to provide some evidence as to the boiler sizing rationale. The report provided details of the heating load requirement for the PFI development, stating a total heat load of 9,513kW was necessary, and that this had been based on outline design

calculations that includes an 8% uplift to account for heat distribution losses. No engineering calculations or decision process notes were provided in support of these figures. The report also made clear that no heat load allowance had been made for the site retained estate, nor the Trust owned maternity and oncology new-builds. From interview transcripts, it is understood that the final boiler capacity requirement specified by the PFI project team for the ‘PFI development’ only, was 12 MW, and despite the Trust engineering team challenging this at the time, the PFI project team were adamant and uncompromising. Despite the Trust taking advice, due to the risks associated with not meeting their contractual obligation (i.e. to provide enough heat to the PFI installation) and secondly, to ensure the PFI programme was not delayed, the 4 MW boilers were removed, and replaced by three 8.2 MW boilers, having a total installed capacity of 24.6 MW. From discussions with Trust staff [Interviews - P3, P4, P10] it is understood that total current peak thermal demand for the Royal Stoke Hospital site is between 5 and 6 MW during winter, from a combination of old and new Trust retained buildings, and newly constructed PFI estate. A recent addition to the heating system is a combined heat and power (CHP) unit that provides a further 1.4MW thermal capacity to the site.

The boiler house design was undertaken by an engineering consultancy, engaged by the Hospital Trust. As discussed, the key influence leading to the significant oversizing of the boiler house was due to the capacity requirements specified by the PFI design team, prior to the construction of the new PFI hospital, but in addition to the further N+1 redundancy factor that was then applied by the boiler house design team [Interview - P10]. N+1 redundancy is a form of resilience that ensures system integrity in the event of component failure or during maintenance downtime (the redundancy of a single boiler [N] is substituted by a boiler of matched capacity [+1]). Taking into consideration the additional thermal requirement of Trust retained buildings, there is a consensus amongst those staff interviewed, that the boiler design sizing rational was based on the fact that two, 8.2 MW boilers would adequately satisfy the anticipated thermal requirement of 16 MW (12 MW for the PFI building + 4 MW for trust retained buildings) and a third 8.2 MW boiler would provide a N+1 redundancy factor, should one of the two duty boilers become unavailable. The existing boiler house setup is illustrated in Figure 1.



**Figure 1. Royal Stoke hospital boilers - installed capacity vs. site max thermal load**

## 5. Design margins and the correlation to building energy performance

This section aims to provide illustrations that support the notion that “system overcapacity resulting from the over-design of building services leads to a general reduction of system energy performance”. The key scenario discussed within this paper is that of the Royal Stoke University Hospital boiler house, however, it is the professional experience of the author from a 30-year career in building services energy management and from a building services design consultants perspective [Interview - P11] that energy

infrastructure overcapacity, is a common scenario. This is also supported by research into energy infrastructure and the healthcare environment, which find oversizing is both common and challenging to rectify [Peeters et al. 2008], [Djunaedy et al. 2011], [Bacon 2014]. Oversizing is found throughout building services design, which not only affects many boiler systems but many other building service systems too, such as; comfort cooling units (DX refrigeration units), water chillers, distribution pumps, calorifiers and mechanical ventilation systems.

Firstly, the empirical evidence is examined based upon Interviewee number 11, a Chartered Design Consultant and the author's own experience (Interview - P11). Importantly, this evidence builds upon and supports the research by Bacon in the healthcare environment and Djunaedy et al. and Peeters et al. in other sectors [Peeters et al. 2008], [Djunaedy et al. 2011], [Bacon 2014]. A second example of system overdesign is that of hospital mechanical ventilation systems, an issue that is very often prevalent in new hospital buildings, but also applies to other large commercial buildings such as offices [Djunaedy et al. 2011]. The examples below illustrate some of the design requirements, and how the application of margins manifest, resulting in a negative impact on system efficiency.

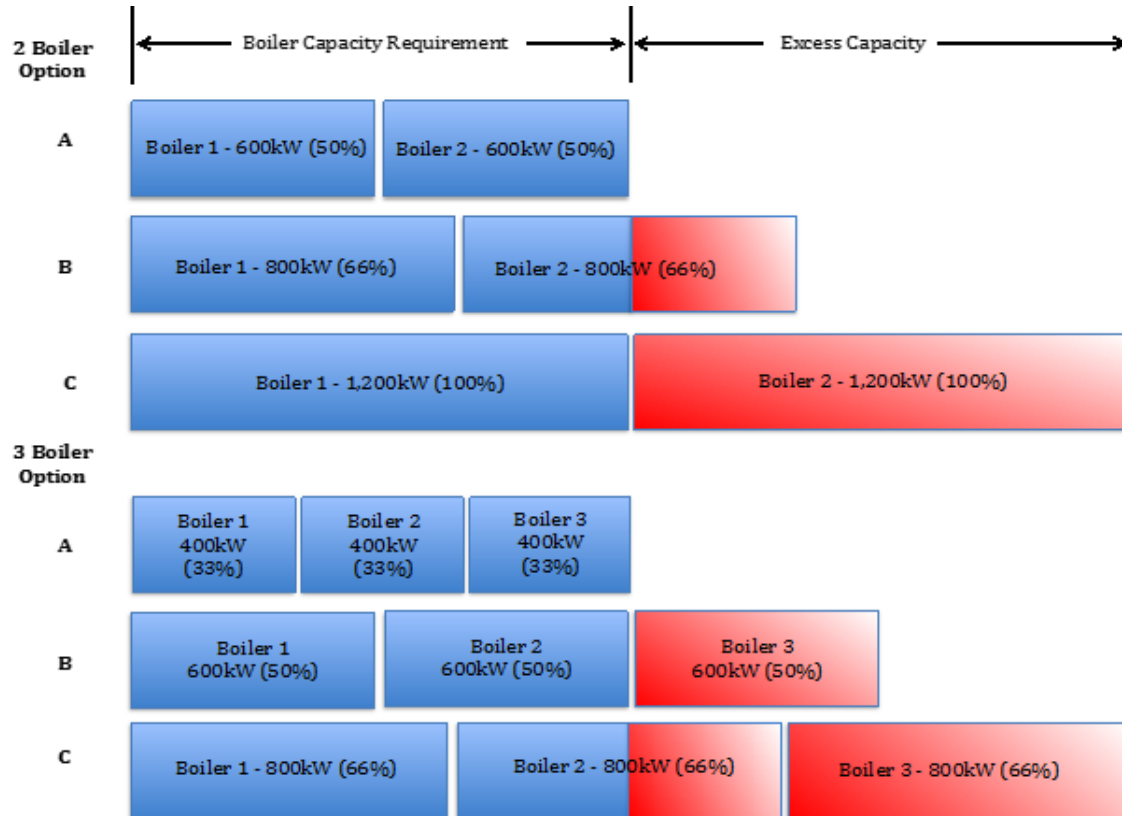
### 5.1 Energy infrastructure oversizing - empirical evidence

The design process for the implementation of energy infrastructure follows certain rules and heuristic decision-making practices; a trade-off between risk and certainty. It is generally accepted amongst building service design engineers that preliminary designs should have an accuracy of plus or minus 25%, design development should have an accuracy of plus or minus 15% and that production information should have an accuracy of plus or minus 5%. For a multitude of reasons these target margins are not always realised [Interview - P11]. This is supported by the research by Djunaedy et al. in 2011, which shows that many design decisions are based upon previous experience and rules-of-thumb, ultimately adding cost for the client [Djunaedy et al. 2011]. Bacon in 2014 also supported the view that conventional building design "grossly over-estimates occupancy leading to... ..poor energy and carbon performance" [Bacon 2014]. Design margins will be applied throughout the design process, from many of those involved; these will include strategic decision-makers in the case of healthcare, often without full technical knowledge, and the technical design team. As the case study showed, the technical design team did not need to fully justify their initial figures, despite some resistance from the Trust, ultimately leading to a significantly higher than required starting point. It is not known how much consideration of future trends in healthcare, or legislative energy targets, influenced the early specification of the case study. Understanding and fully considering these initial design choices is important; errors here can significantly impact decisions further down the design process, hindering rectification efforts without major design changes.

However, once an initial specification is confirmed, more detailed design can go into the system choices. In the case of a boiler design scenario, choices regarding the number of boilers detailed will determine how many margins are added overall. For example, in apartment blocks, commercial and industrial applications, more than one boiler is used. If a design load is 1,200kW then 2 No 600kW boilers could be used (2 x 50%), or 2 No 800kW boilers could be used (2 x 66%), or 2 No 1,200kW boilers could be used (2 x 100%). All three choices could be correct depending on the application, and how critical it is to maintain the load. As an alternative, three boilers could be chosen. This would give rise to 3 No 400kW boilers (3 x 33%), or 3 No 600kW (3 x 50%), or 3 No 800kW boilers (3 x 66%). In the above, the capability of the installation as a percentage of the design boiler load (kW) varies from 100 % to 200%; the above scenarios are illustrated in Figure 2.

This is a large capacity spread and a number of design margins would be considered, particularly those relating to cost and functionality of the building or the space available for the installation. An alternative method of design to that illustrated in Figure 2. specifies different boiler sizes to create agility in working practice. For example, boiler 1 would have an output of 200kW, boiler 2 would have an output of 400kW and boiler 3 would have an output of 600kW collectively to meet the 1,200kW capacity requirement. In this way, it is more likely that the output to the building can be matched to what is required; hence smaller burners are able to modulate with their range. The correct boiler to operate will be chosen; a different boiler at different times to suit the required load. This prevents the boilers from cycling on and off, reducing their life and operating inefficiently. It is often the worst-case scenarios, which are

designed for; in the case of buildings this will include assumptions about heat loss through the building fabric or air infiltration. However, in many cases heat gain is not calculated for and in the case of hospital environments this can be very significant. Medical and computing equipment, non-LED lighting and human occupants will all add to the heat output in the building; MRI scanners emit so much heat that they need permanent cooling. Proper consideration of these elements would better improve the boundaries of the design margins added.



**Figure 2. Illustration of correct sizing options for a 1,200kW boiler installation**

### 5.2 Example 2 - ventilation system overdesign

The absorbed fan power of ventilation systems in modern hospitals account for up to 12% of the total hospital electricity usage [Carbon Trust 2010]. The predominant design capacity criteria for any given hospital ventilation system is based upon the number of air change rates (ACRs) required, dictated by Health Technical Memorandum 03-01: Specialised ventilation for healthcare premises - Part A: Design and validation, Appendix 2 [Department of Health 2013]. For non-health buildings, the predominant sizing criteria for ventilation systems is maximum occupancy numbers, to which, a measure of 10 litres/sec of fresh air, per person is applied [Chartered Institution of Building Services Engineers 2006]. Other design criteria such as internal and external design conditions, air purity, humidity requirements, noise levels etc. will also need to be considered.

A hospital design scenario will require a ventilation fan to be selected that meets the minimum air change rate requirement; for general areas this is 6 AC/hr. [Department of Health 2013]. Each fan has an inherent capacity range and optimum efficiency point that is dependant on system pressure. Because exact system pressure is difficult to deduce at the design stage, fan units selected are typically oversized to ensure required air-flow rates can be met, in situation of worse case scenario. Once selected, a fan will require a drive motor that is capable of meeting the absorbed power requirements of the system. Motors are only manufactured in certain capacity ranges; therefore as an example, a fan having a specific power requirement of 11.5kW would require a 15kW motor to be fitted (available motors capacities in



this range are 11 and 15kW). Even if a motor is available to meet the exact power requirement of the fan, a safety margin of up to 25% is typically applied. This results in a system design that is significantly oversized, however, because the ventilation system can easily and effectively be commissioned using a variable speed drive (VSD), to modulate fan speed down to required duty point, the delivery of the design operating requirements (such as air-flow) can be met. This however, is often to the detriment of power efficiency, whereby the fan itself is not operating at its optimum efficiency point, and secondly, the motor absorbed power is far less than its design capacity. It is the authors experience that drive motors on ventilation systems typically only operate at 50-70% load; this results in poor power-factor loading on the motor and hence, reduced power efficiency. It is not atypical for a newly commissioned ventilation system therefore, to be operating at efficiencies, 20-40% below optimum.

## 6. Conclusions and further work

It is clear from this case study, which supports other related research, that there is a need to challenge design assumptions and margins. Where there is a specific need to be more energy efficient there is also potential for cumulative design margins, added by different decision-makers throughout the process, undermining overall efficiency. The case study showed that an initial calculation, not challenged by strategic, non-technical decision-makers, provided a basis upon which further margins were added. Whilst elements of margins are required to provide resilience and to ensure that future capacity needs are met, it is clear that current design practices do not account for the cumulative effect of additional margins. Where margins are applied to each stage of the design process there is a tendency for the overall system to be designed with significant overcapacity. This causes an inherent efficiency issue, as the oversized system is then incapable of operating, at its optimum point, as shown in previous research [Peeters et al. 2008], [Djunaedy et al. 2011]. It is particularly relevant to energy efficiency, which should be considered as part of future proofing any design to meet the needs of resourcing challenges and attain a low energy future.

Ensuring that energy efficiency is prioritised throughout the design process, as described by the Albers et al. 2015 model, will test heuristic design margins [Albers et al. 2014]. It is therefore an absolute necessity that we consider and apply margins systematically and manage the design processes effectively to ensure building services systems not only meet current and future requirements, but do this without compromise to system energy performance. The key issue highlighted in the Royal Stoke University Hospital boiler house case study, was that the fixed PFI contract specification in respect to the required thermal capacity requirement was not successfully challenged or understood by the Trust or boiler house design team. Better communication of the design margins applied and their reasoning early in the design process, particularly to non-technical strategic decision-makers, is needed to manage overall effects. Bacon also concluded that “a detailed understanding of how the hospital would be used and by using this new knowledge to provide the engineering team with the information that they required to avoid the substantial assumptions that are often made both in the design of the facilities engineering systems as well as the systems to control them” [Bacon 2014].

There are differences in the technical language understood and applied between engineering designers and strategic decision-makers. From the case study, it was unclear whether the specified capacity of 12MW included or excluded a redundancy factor, and what other engineering margins were applied. Design margins are often hidden or unknown by multiple project stakeholders groups, and the full understanding is somewhat localised, and not explicitly communicated. Buffers such as safety margins and redundancy for resilience, engineering over design and future proofing needs, all create system excess and uncertainty that need to be addressed cumulatively as part of the design process. Future work will therefore aim to identify and compartmentalise the numerous margins associated with building services design and provide a quantitative measure, and method, that will help mitigate against the extent to which a engineered system exceeds what is necessary to meet its functional requirement. Translating the addition of design margins into non-technical language will also be important so that strategic decision-makers can better gauge the requirements prior to specification and make judgement on technical specifications.

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