UCL Institute for Environmental Design and Engineering

Circular options for building services: Case Studies; 22 Gordon Street, Arup Circular Building

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Executive summary

The circular economy concept has gained momentum over recent years, but few have analysed its application to the building services sector. This project aims to contribute to unravelling this opportunity (and its constraints) as a joint interest between UCL IEDE, UCL Estates, and Arup, to create useful guidelines for the industry.

Building services fall within the ‘sweet spot’ for applying circular economy strategies. Some of the sector’s biggest issues such as; specialty equipment with high (upfront) costs, fast obsolescence, maintenance issues and costs, and the well-known performance gap can be dealt with by applying some of the strategies discussed in this report.

Using the Ellen MacArthur Foundation’s building blocks and ReSOLVE levers framework, the CIBSE TM56 report on Resource Efficiency in Building Services, and circular case studies found in the industry, this paper sets the base to understand the application of circular economy to building services.

Two case studies are analysed: 22 Gordon Street, as a business-as-usual design and construction project with a standard RIBA stages process and The Circular Building by Arup, as a temporary test lab where circular strategies were tested and products assembled together and successfully dismantled at the end of use. Interviews were carried out with four decision-makers involved in the design of 22 Gordon Street and three in The Circular Building to understand the decisions (and reasons) that influenced the selection of certain building services and their circularity according to the previous literature guidelines reviewed. Supporting design documents were then studied to understand the ordinal relationship between decisions and the stage at which these were taken.

For 22 Gordon Street it was found that the client’s (UCL) complex mix of internal bodies had the greatest influence in driving decisions through its managerial Estates department, facilities manager, BSA representative and technical team. Some of the decisions that most influenced building services and their circularity were not directly connected: the drastic change of brief and project scope, extending the building by two storeys, the specific architecture teaching space planning requirements and variety of users, the retention of the concrete frame and the design of the open atrium stairs. These and other building performance drivers led to the selection of the following key services solutions: a complex air-conditioning user control strategy, a centralised HVAC system with local multi-purpose chilled beam units, the resolution to install a new high voltage transformer, integrating the LED luminaires into the chilled beams, high-quality ‘gender-neutral’ toilets, a centralised DHW system, the need for a fire-dedicated core and other fire-safety services (a sprinkler system was not required) and the decision to avoid installing an extra lift.

On the other hand, The Circular Building demonstrated current methods of applying circular strategies to construction and building components. The most successful building layer in terms of circular economy was found to be the Accoya timber façade, and the following findings arose from choices made for its circular building services: digital material passports and the use of BIM, a 3D printed MVHR unit, sustainable Gatorduct cardboard ducts, a DC power network provided by a saline battery, plug-and-play power connections, recyclable Xicato LED lighting modules and a virtual controls system using Wi-Fi and IoT data monitoring.

Decision-making guidelines and a new RIBA Plan of Work are proposed to aid the design and procurement of circular building services. Conclusions identify two key drivers to accelerate the transition to a circular economy: better information gathering through digital technology, and business models shifting towards service/performance-based contracts.

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GLOSSARY

AHU: Air handling unit

AI: Artificial inteligence

BIF: Bartlett Innovation Fund

BIM: Building information modelling

BMS: Building management system

BREEAM: Building Research Establishment Assessment Method

BSA: Bartlett School of Architecture

CE: Circular economy

CIBSE: Chartered Institution of Building Services Engineers

CircEL: UCL Circular Economy Lab

CNC: Computer numerical control (cutting machine)

CO_2: Carbon dioxide

C2C: Cradle to Cradle

DAS: Design and Access Statement

DC: Direct current

DGBC: Dutch Green Building Council

DHW: Domestic hot water

DLS: Homij's in-house BIM library

EMF: Ellen MacArthur Foundation

EM&I: UCL Engineering, Maintenance & Infrastructure department

GHG: Greenhouse gas

HVAC: Heating, ventilation and cooling

IoT: Internet of things

ISD: UCL Information Services Division

LCA: Life cycle assessment

LED: Light-emitting diode

MEP: Mechanical and electrical plant

PIR: Passive infrared sensor

PV: Photovoltaic

P2P: Peer to peer

RIBA: Royal Institute of British Architects

ROI: Return on investment

RTH: Refrigeration Ton hour (1RTH = 3.5 kWh)

UCL: University College London

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Background to the project: UCL East, Marshgate Building and Arup's investigation

Arup is currently immersed in ongoing research focusing on what circularity could mean for building services in the proposed UCL Marshgate building, CE principles have been captured by 5 scenarios 5 possible CE scenarios have been developed and are being considered:

- **Universal building**: building layout and systems to be designed to maximise flexibility and ease of conversion for future uses.
- **Pre-loved**: all MEP systems and equipment used must be pre-used or recycled.
- **Passive-only**: minimise use of active MEP systems by aiming for purely passive solutions.
- **Joint Venture**: MEP as a service: client employs joint venture to design, build, operate and maintain systems for an upfront fee and an ongoing retainer dependent on performance. One reason for the performance gap in MEP is when the interests and motivations of the different stakeholders do not align, so they are not designed for each other. So, by the time the product/component is installed, there are problems even if everyone along the line has done a perfect job. Service/performance contracts could change this situation and enable circular decisions by changing the incentives.
- **Self-sufficient**: consider the building as a self-sufficient independent system.

The hypothetical resulting building could sit in any of these scenarios which are at the edges of a larger problem space.

For each scenario, life cycle cost and carbon have been calculated for comparison. The value of each strategy is particular to the Marshgate building and cannot necessarily be generalised.

While Arup's investigation focuses on what circularity means for buildings and their services, this report analyses how the decision-making behind a design and procurement process must change to enable it. The hypothesis is that there is an optimum time to decide MEP system options during the design process and that, at certain points, decisions made have definitive consequences on the 'circularity' of a building; impacting on life time carbon emissions, cost, energy consumption, performance, adaptability, material use and the ecological footprint of the building.

1. Introduction, aims and objectives of the project

This report, is the output from a project idea, which received a Bartlett Innovation Fund grant to explore issues around how to use the UCL estate to test ideas on circular economy and building services. The project was a collaboration between UCL's Institute for Environmental Design and Engineering (IEDE), Arup and UCL Estates. One aim was to investigate decision-making that would lead to more "circular economy"-based decisions related to HVAC systems selection in non-domestic buildings. The research was carried out by Ramon Mendoza, a Masters student on the MSc Environmental Design and Engineering programme, and formed the majority of his dissertation project, which was jointly supervised by Croxford, Rovas and Portal.

The circular economy is a concept aimed at keeping resources in use for as long as possible at their highest possible utility and has recently been strongly promoted and supported by the Ellen MacArthur Foundation. They have been concerned particularly with plastics and textiles (EMF, 2017c, 2017a). In this project we consider building services, a sub-section of the built environment in general, which are often replaced when buildings are refurbished. A PhD student, Miguel Casas, supervised by one of the authors, Croxford, has been focussing on circular options for building fit outs. This highlighted an under-researched area for Circular Economy thinking, that of the design and procurement of Building Services and within that, particularly looking at Heating, Ventilating, and Air Conditioning, (HVAC) systems.

For this project, the team selected two case study buildings: (i) 22 Gordon Street (22GS), where we had excellent access to the full design team, and (ii) Arup's Circular building, a small demonstration pavilion that was built for an exhibition outside the Building Centre in Store Street.

The plan was to identify and interview key stakeholders that participated in the design process and gather information that could lead to us being able to map out the timelines for the various decisions taken according to the RIBA plan of work and produce guidelines to help design teams review more circular options for building services during building design. The objectives, in order of action, were:

- Understand how circular economy principles apply to building services and the level of implementation in the sector.
- Identify key stakeholders and their decisions influencing MEP system selection and circularity for both case studies.
- Generalise results to create a generic timeline/guideline that can be used by UCL and the industry to help develop more circular buildings and MEP systems.

To achieve these, the report aimed to answer the following questions:

- What does circularity mean for the building services sector? What are the drivers and barriers?
- What decisions to improve circularity must be taken at each stage and by whom? When is the optimal stage for the contractor and suppliers to get involved to aid these decisions?
- How must circular building services be specified and what criteria hierarchy should be used to procure them given the immaturity of the circular market?
- Which business models and contractual relationships are best suited for the circular economy? How can supply and maintenance contracts work?
- How can these findings be used by UCL and the industry in future buildings?

In the process of this project we have created a network of contacts that can help with information transfer and could influence future UCL and Arup buildings.

This report is structured with a literature review, a methodology for the study, a results chapter presenting the findings from the interviews, a discussion chapter synthesising the findings into design guidelines and a final chapter with conclusions and future recommendations.

2. Literature review

2.1. Building services and their carbon footprint

Building services have become essential for ensuring the correct functioning of modern buildings, but they are also responsible for a significant part of their operational energy consumption and carbon footprint. These systems are often high cost, need maintaining regularly and occasionally replacing, so their total life time cost over the life of the building can be significant (Cheshire, 2014).

Until very recently, policy and legislation efforts towards zero carbon buildings have been narrow-sighted, focusing only on emissions arising from their operation (DCLG, 2007), this is changing, as operational emissions are falling the focus is shifting to also consider embodied energy. Building services have a significant impact on all stages of life cycle emissions: raw materials extraction, manufacturing process, construction, use (including maintenance and replacement) and end of life disposal (Cheshire, 2014). Progressive reductions in operational carbon footprint, more energy efficient MEP systems and higher embodied carbon in renewable technologies are rebalancing the traditional split between operational and embodied carbon in buildings. Indicative percentages estimated for different types of buildings by Sturgis Associates LLP can be seen in Figures 2 & 3. Figure 2 is based on average calculations of buildings designed at present and Figure 3 on future buildings as a result of existing and forthcoming legislation aimed at reducing operational carbon emissions down to zero.

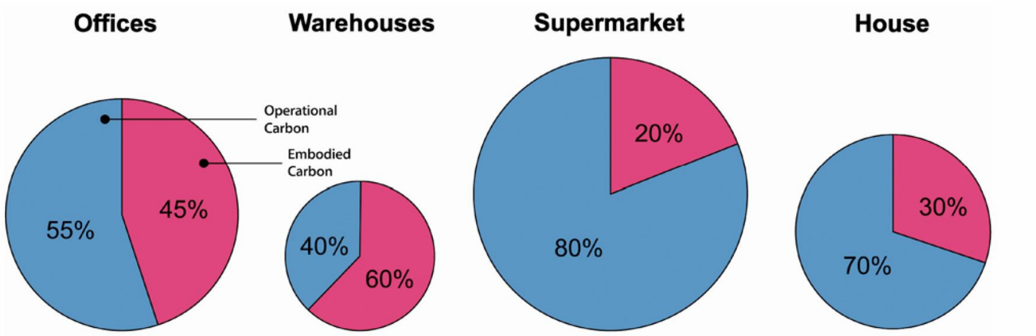

Figure 1. Typical different Whole Life Carbon splits for different types of buildings at present
Source: Sturgis Associates LLP Indicative Whole Life Carbon Emissions (2011)

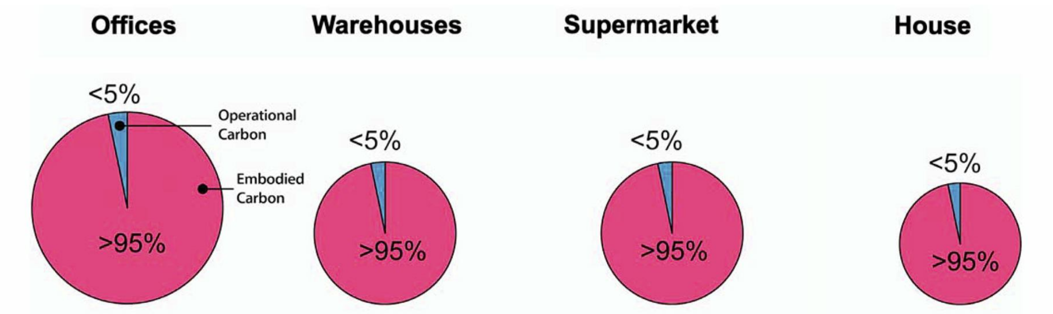

Figure 2. Expected typical Whole Life Carbon splits for different types of (new) buildings in 10 years time
Source: Sturgis Associates LLP Indicative Whole Life Carbon Emissions (2011)

Another study by Davis Langdon on the embodied carbon of 30 new-built offices shows values of about 600 to 1200 $kgCO_2eq/m^2$ while operational carbon emissions are in the region of 20 to 75 $kgCO_2eq/m^2$ per year. On this basis, initial embodied carbon is typically equivalent to around 20 years of operation (Hitchin, 2013).

The combined weight of MEP services in the initial embodied carbon of buildings differs greatly between studies. CIBSE Research Report 9's effort to estimate this figure shows a range of 18-240 $kgCO_2eq/m^2$ (2-25% of the total initial embodied carbon) for office buildings and around 24 $kgCO_2eq/m^2$ (8%) for housing (Hitchin, 2013). The main reason for the discrepancy being between air conditioned, highly-serviced office buildings and naturally ventilated ones.

This proportion increases over the lifetime of a building, since MEP equipment needs high maintenance and its average lifespan is relatively short: between 5-35 years depending on the system. Figure 4 shows lifespans of different components in a typical office building: toilets and cooling systems are amongst the shortest, then ventilation systems and finally electric systems, lifts and AHUs can live up to 35 years (McIntosh and Roberts, 2012).

Figure 3. Average lifespans of components within an office building. Source: Sturgis Associates LLP (2009)

As the 'recurrent' embodied carbon of building services can be 3 times more than the initial value and double the average building component, their lifetime embodied carbon can grow from an initial 10% to a final 20% of total building embodied carbon as seen in Figure 5 (Cheshire, 2014).

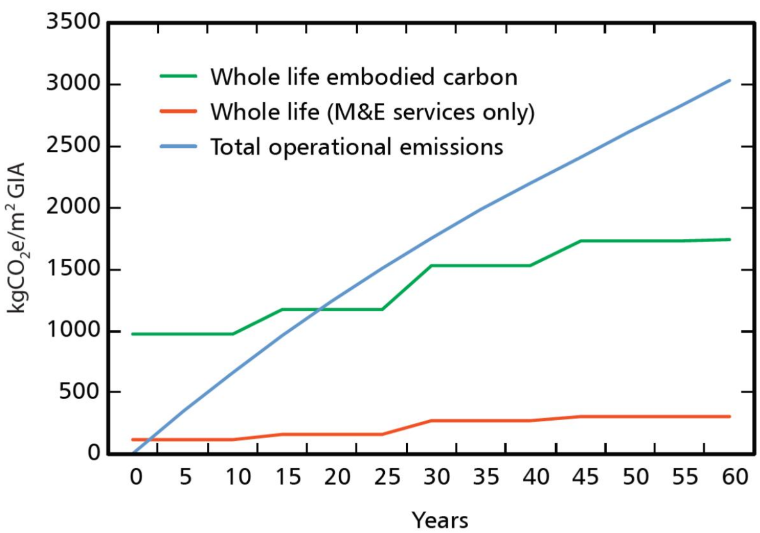

Figure 4. Whole life embodied carbon of a 60 year old building and its M&E services vs operational emissions. Source: CIBSE TM56 (2014)

From the same study by Davis Langdon, a breakdown of building services' embodied carbon of a case study London office is shown in Table 1. HVAC and electrical installations represent around 1/10 of a building's total value and 2/3 of all building services', but these figures largely vary depending on the systems included (mainly HVAC) and the materials used for the circuits (ducts, pipework and wiring) (Hitchin, 2013).

Table 1. Example breakdown of building services' embodied carbon in a London office. Source: (Hitchin, 2013)

Building services	**Embodied carbon (kgCO2eq/m²)**	**% of whole building value**
Water installations	1.1	0.13%
Space heating and air treatment	48.61	5.81%
Electrical installation	46.08	5.51%
Lift and conveyor systems	19.42	2.32%
Protective installation	11.19	1.34%
Total	**126**	**15%**

2.2. Circular economy and building services

Building services systems have a significant weight on buildings' whole life cycle emissions and operation costs. Expensive equipment and components have a relatively short life and are generally discarded and replaced at the end of life. This, added to the performance gap between designed and installed MEP systems, place building services within a 'sweet spot' for applying circular economy principles. Figure 6 shows how the usual make-use-dispose linear model could be replaced by a closed resource loop circular model. As Nick Cliffe from Innovate UK states, "in the built environment, it's all about maximising utility of resources - extending product life or providing a proper end-of-life recovery".

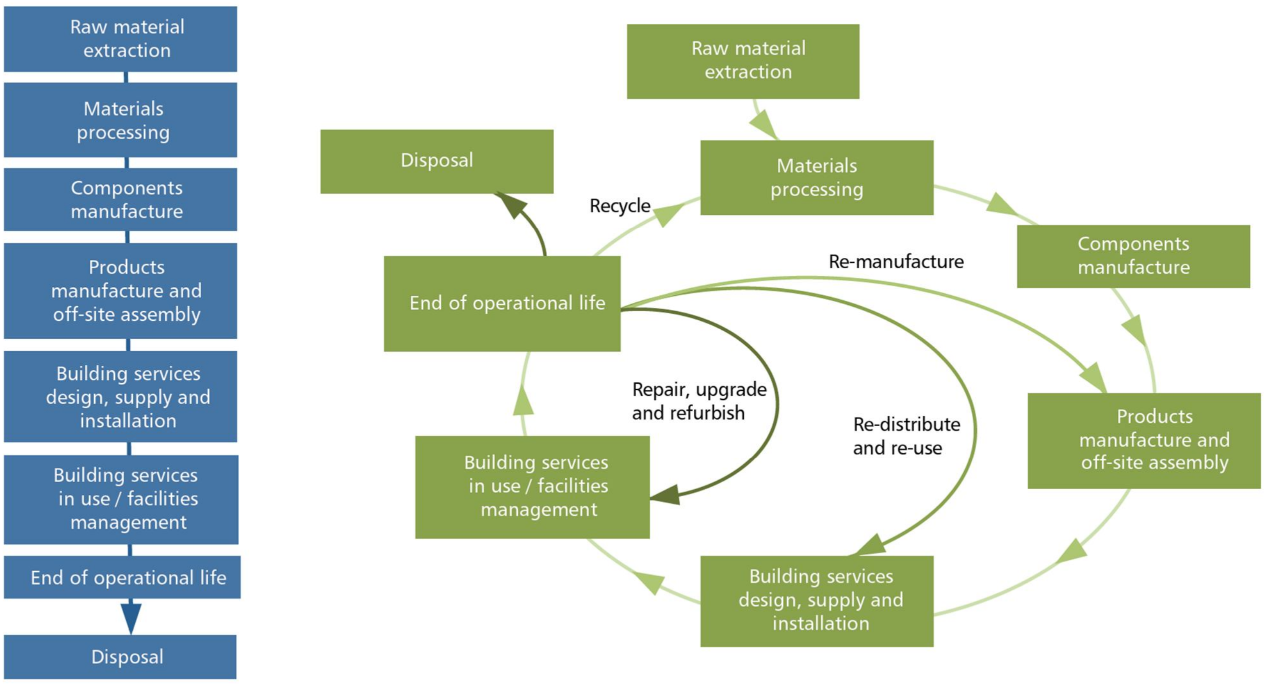

Figure 5. Simplified comparison of a linear (left) and a circular economy (right) for building services
Source: TM56: Resource Efficiency of Building Services (Cheshire, 2014)

To enable this transition to a CE scenario, designers need to acknowledge that buildings cannot be conceived as a homogeneous entity but rather as a set of interlinked layers of components that operate at different timescales, evolve differently and should be upgraded or replaced independently. This 'Shearing Layers' concept was developed by Frank Duffy and later elaborated by Stewart Brand in his book, *How*

Buildings Learn: What Happens After They're Built (Brand, 1994). The original concept included 6 layers and Arup later added the 'System' layer to create the 7S Model shown in Table 2 and Figure 7 (Arup, 2016b).

Table 2. The 7S Model / Shearing Layers. Adapted from: The Circular Economy in the Built Environment (Arup, 2016b)

SYSTEM	• Includes the structures, services and resources external to the building that facilitate the overall functioning: roads, railways, electricity, water and waste water systems, telecommunications, parks, schools, digital infrastructure...
SITE	• Fixed location of the building, whose boundaries and context outlast generations of ephemeral buildings. • "Site is eternal." (Brand, 1994)
STRUCTURE	• The foundation and load-bearing elements are enduring elements. Buildings can completely change their appearance and use without changing their structure. • Replacement every **30-300 years**
SKIN	• The external envelope can change to adapt to aesthetics, new technology, better daylight, energy efficiency or repair. On occasions, façade replacement can reduce operational carbon to the extent of outweighing the extra embodied carbon incurred. • Replacement every **~20 years**
SERVICES	• Includes all systems that that operate the building: communications wiring, electrical wiring, plumbing, fire sprinkler systems, HVAC (heating, ventilating, and air conditioning), and moving parts like elevators and escalators • Replacement every **7-15 years**
SPACE	• The Interior layout affecting the location of partitions, ceilings, floors and doors • Commercial space can change every **3 years**. Homes can extend to **30 years**
STUFF	• Furniture, appliances, fixtures, etc. It can be moveable or fixed • This changes from a **daily to monthly basis**

Building services constitute a particularly important layer in this concept as they wear out or become obsolete every 7-15 years but are sometimes deeply embedded within the long-lasting layers. Building services and other 'fast-pace' layers should be designed and fitted independently to the 'slow-pace' ones, such as the structure, to allow easy servicing and replacement, and avoid unnecessary demolition.

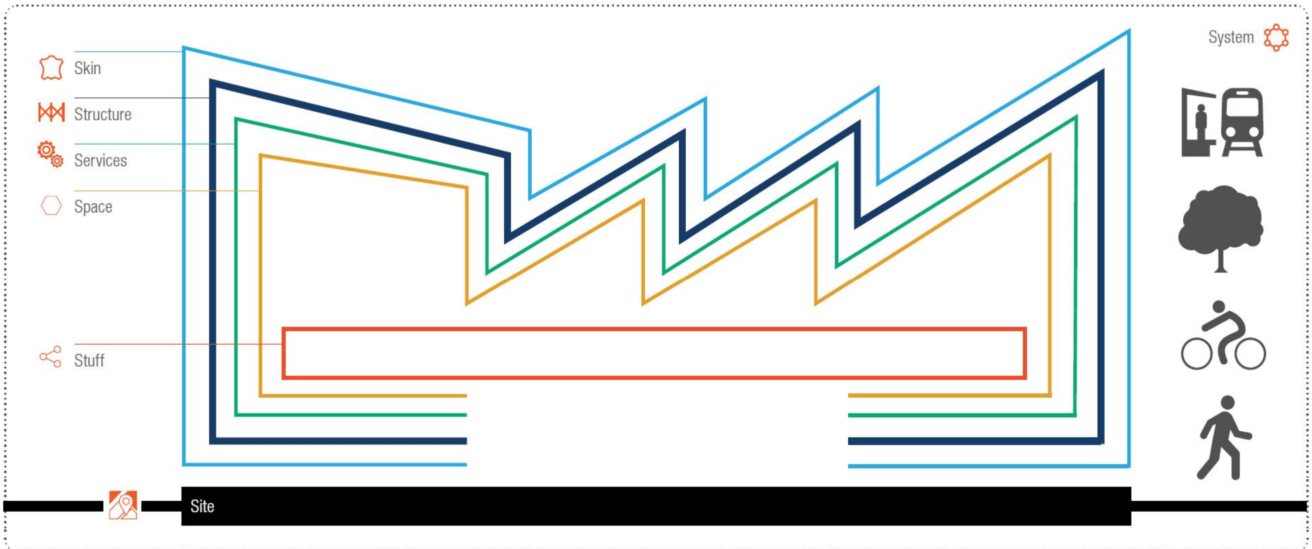

Figure 6. The 7S Model. Source: The Circular Economy in the Built Environment (Arup, 2016b)

A transition to a circular economy requires the transformation of the whole supply chain behind building services systems and components. The Ellen MacArthur Foundation has developed a universal framework applicable to all sectors of the economy consisting of 4 'building blocks' and the 6 ReSOLVE Levers.

Table 3 describes the 4 'building blocks' driving change to all sections of the supply chain (EMF, 2015).

Table 3. Ellen MacArthur Foundation's 4 building blocks driving the change to a circular economy (EMF, 2015).

Building block	**Description**
Circular design (design & manufacture)	Product design must be rethought to take into consideration whole life stages such as reuse, maintenance and repair, refurbishment, remanufacture and, finally, recycle. New skills and collaborative working methods are needed, but technologies such as 3D printing, BIM[1] software, BMS[2] and other data processing programs can enable this.
New business models (service & finance)	Ownership models are replaced by service or performance contracts that can help align economic and environmental interests and encourage greater levels of corporate responsibility.
Reverse cycles (reverse logistics)	New technology, industries and businesses must arise or be reinforced to enable efficient closed loop cycles.
Enablers and favourable system conditions	Including education, finance stimuli and government policy among others.

Closely related to this, the ReSOLVE Levers are 6 system-wide strategies to transition to a circular economy. "In different ways, these actions all increase the utilisation of physical assets, prolong their life, and shift resource use from finite to renewable sources. Each action reinforces and accelerates the performance of the other actions, creating a strong compounding effect" (EMF, 2015, p. 26). Table 4 shows how each one represents technologies in development, and presents circular business opportunities for all stakeholders.

Table 4. EMF's ReSOLVE Lever framework applied to building services
Adapted from: Growth within: a circular economy vision for a competitive Europe (EMF, 2015)

REGENERATE	• Shift to renewable energy (**PVs, passive solar, natural ventilation, free cooling**...) • and materials (**timber, cardboard, bioplastics**...) • Reclaim, retain and restore health of ecosystem (**water filtration, cleaning air**...)
SHARE	• Share assets (**district energy, P2P trading, waste heat, equipment, space**...) • Reuse/secondhand (**reuse ducts, pipes, equipment, space**...) • Prolong life through maintenance, design for durability, upgradability, etc.
OPTIMISE	• Increase performance/efficiency of product (**AI, BMS, flexible design...)** • Remove waste in production and supply chain (**BIM, local sourcing, 3D printing**...) • Leverage big data, automation, remote sensing and steering (**big data, robotics**...)
LOOP	• Remanufacture products or components (**design for disassembly and upgrade**) • Recycle materials (**use recyclable materials**) • Digest anaerobically (**from sewage water or waste food**) • Extract biochemicals from organic waste (ditto)
VIRTUALISE	• Dematerialise directly (**controls and switches, PIR, BMS**...) • Dematerialise indirectly (**product marketplaces, transactions, design, BIM**...)
EXCHANGE	• Replace old with advanced non-renewable materials (**nanotechnology, graphene**...) • Apply new technologies (**3D printing, laser cutting, robotics, BIM, BMS, PIR**...) • Choose new product/service (**product as a service, multi-function equipment**...)

[1] BIM: "Building Information Modelling and Management is digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition." (BIM Industry Working Group, 2011)

[2] BMS: "The term BMS refers to a system where components are able to communicate with each other and generally implies some form of central supervisor, which permits monitoring and control of the building from a single point." (CIBSE, 2009)

Finally, based on WRAP's guidelines, CIBSE TM56 paper addresses resource efficiency in building services. A set of actions affecting both design and plant and equipment specification are summarised in Table 5, though a more exhaustive discussion, including industry case studies, can be found in the original document (Cheshire, 2014; WRAP, 2014).

Table 5. Opportunity actions to improve the resource efficiency of building services. Source: CIBSE TM56 (Cheshire, 2014)

Action/strategy	**Description**
Passive design: 'designing-out' the need for plant and equipment	The aim is to eliminate the need for some building services such as thermal conditioning by using passive design strategies. Future variation in building use or climate change may discourage this option.
Changing designs to be more resource efficient	Use less material, improve operational performance and overall environmental impact of the system. E.g. Kone has developed a new carbon fibre core rope which is considerably lighter than existing steel ropes, doubles the lifetime and does not require lubrication
Safeguards against premature or planned obsolescence	- *durability*: by identifying likely failing components or monitoring the equipment to provide condition-based maintenance. - *modular and adaptable design*: to allow future upgrades, improve on the original design and replace worn components. - *cascading*: find new users for the product in its current condition or partly upgraded.
Use of Building Information Modelling (BIM)	To increase resource efficiency and reduce wastage through clash prevention, increased precision and coordination at both design and construction stages
3D printing (additive manufacturing)	Avoids yield losses associated to off-cuts, machining, stock accumulation and conventional manufacturing defects. E.g. Monodraught has been able to reduce the number of components in their cooling systems by 70% by using 3D printing technologies.
Design for off-site construction	Requires a high level of planning and coordination but can increase quality, precision and avoid wastage. E.g. off-site ductwork, bathroom pods, prewired pumps sets…
Recycled content	Can reduce the demand for virgin materials, but it should not increase the operational efficiency of the components. E.g. Prihoda has designed fabric ductwork made from 100% recycled post-consumer plastic bottles
The standardisation of products and systems	Allows components to be replaced easily. E.g. The international Zhaga Consortium is developing a standardised interface system to allow the interchangeability of LED light sources.
Design for deconstruction/disassembly	By minimising types of materials and composites, using mechanical rather than chemical connections, and providing permanent material identification and assembly instructions. E.g. Philips is developing a prototype LED lamp designed for disassembly
Label products with a list of materials and components	Allows the contractor responsible for disposing the product and potential buyers to know what can be reused and recycled. E.g. Schindler Environmental Factsheet gives disposal instructions for one of its lifts.
Leasing equipment or services	Leasing or service/performance contracts incentivise manufacturers to produce durable, easy to maintain and replaceable products. E.g. Philips 'pay-per-lux' and Kaer Air are 2 successful examples that will be discussed later in the case study section.
Transport and packaging	Design reusable or recyclable packaging and reducing transport emissions. E.g. Trox UK has developed a foldable plenum that can be easily stored and transported.
End-of-life recovery, reuse and recycling	Reverse logistics should be in place to enable this. E.g. British Gas has set up a contract with DHL to collect and recycle house boilers and associated components.

2.3. Case studies

The level of implementation in building services is still limited, representing a big (economic and environmental) opportunity, but 6 case studies have been identified and are presented here: 3 examine specific manufacturer initiatives, and 3 investigate CE holistic approaches to the design and specification of entire buildings.

2.3.1. Grundfos pump solutions

Danish company Grundfos provides pumping solutions for HVAC and plumbing worldwide and state they have a long history of a sustainability ethos focused on optimizing manufacturing processes and reducing material usage and operational energy consumption (Grundfos, 2017). Table 6 presents an increase of 87% in resource efficiency for their new generation circulator pumps.

Table 6. Advances in resource efficiency between two generations of Grundfos circulators.
Adapted from: Towards Circular Business Models: Experiences in Eight Danish Companies (Guldmann and Remmen, 2018)

	Previous type (kg)	**New type (kg)**	**Difference (kg)**	**Difference (%)**
Cast iron	1.40	0,79	-0,61	-43.57
Tin	3.70	0.32	-3.38	-91.35
Copper	1.20	0.10	-1.10	-91.67
Permanent magnet	0	0.12	+0.12	+100
Aluminium	0.95	0.22	-0.73	-76.84
Plastic	0.21	0.20	-0.01	-4.76
TOTAL	**7.46**	**0.96**	**-5.1**	**-87.13**

Circulators are their most important product, and in general account for approximately 50% of the world pump market. They are currently piloting a take-back program in Denmark to allow the recycling of components. The reverse logistics utilises the same value chain used to sell the products, by inviting installers to return the old circulators to the wholesalers when replacing them. These are then sent to Grundfos to remanufacture or recycle.

Grundfos Service & Solutions program is a service scheme provided with their products that assists with installation, operations, maintenance and replacement. This lowers consumption, makes the system more reliable and incentivises Grundfos to provide long lasting products and efficient life cycle solutions.

At present, the company has developed a Circular Economy department to analyse further business opportunities and is now engaging with a life cycle assessment (LCA) expert and a recycling company that prepares end-of-life dismantling reports for key products. (Guldmann and Remmen, 2018)

2.3.2. Philips lighting 'pay-per-lux' scheme

Dutch multinational technology company Philips (now Signify) is the largest lighting manufacturer in the world. They also claim to be one of the top 10 leading sustainability companies in the world (Signify, 2018).

In collaboration with Turntoo and Rau Architects, Philips developed a lighting performance-oriented business model where a building owner contracts the amount of light needed as a service and Philips arranges the infrastructure to provide it. As Philips retains ownership of all the components and pays for the electricity consumed, it is in their interest to provide the least number of appliances and make them low consuming, enduring and easy to maintain, replace and recycle. On the other side, the customer benefits from low up-front costs, paying only for what they need and a better service. This win-win business model for manufacturer and customer is also in the environment's interest and kickstarts a virtuous circle where the more efficient the product becomes, the more the 3 parties benefit from it.

The system was first tested in Rau Architects' office in Amsterdam resulting in a total energy reduction of 55%: 35% after the LED installation and 20% through ongoing optimisation (EMF, 2017b) (see Figure 8).

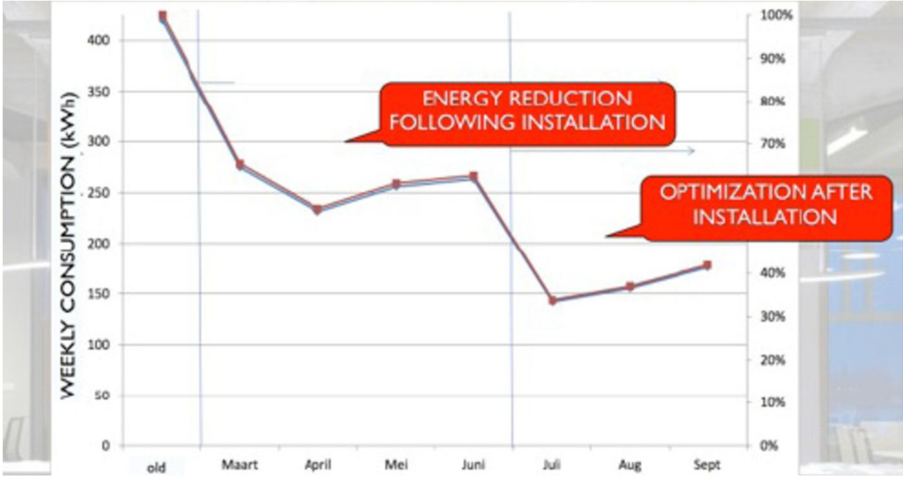

Figure 7. Energy reduction in Rau Architects office before and after Philips' lighting installation. Source: (EMF, 2017b)

The same model has been later applied to Schiphol Airport's Lounge 2 renovation and the National Union of Students (NUS) building in London. Schiphol Airport's installation consumes 50% less power than its predecessor. The new luminaires have a 75% longer lifespan and if a component fails prematurely it can be replaced instead of changing the whole luminaire (Philips, 2017).

2.3.3. Kaer: Air Conditioning as a Service (ACaaS)

Global temperatures are rising and almost half of the population is concentrated in the warm South East Asia region. Consequently, "700 million air-conditioning units are likely to be installed by 2030, jumping to 1.6 billion by 2050", increasing demand for energy and material resources for unit manufacturing, (Kaer, 2017).

Kaer is a multinational 'Air Conditioning as a Service' company based in Singapore providing cooling to over half a million square metres of space across Asia. Similarly to Philips' model, they design and retain ownership of the system, constantly optimising it through IoT technology and AI data analytics (Figure 9). The service is provided with no upfront cost and the building owner simply pays a fixed monthly fee or a pay-as-you use \$/RTH[3] rate. Kaer is responsible for all costs associated with running the air-conditioning system including the electricity used by the chiller plant equipment, repairing and recovering components at the end of life.

[3] RTH: 1 Refrigeration Ton Hour is an energy unit equivalent to 3.5 kWh

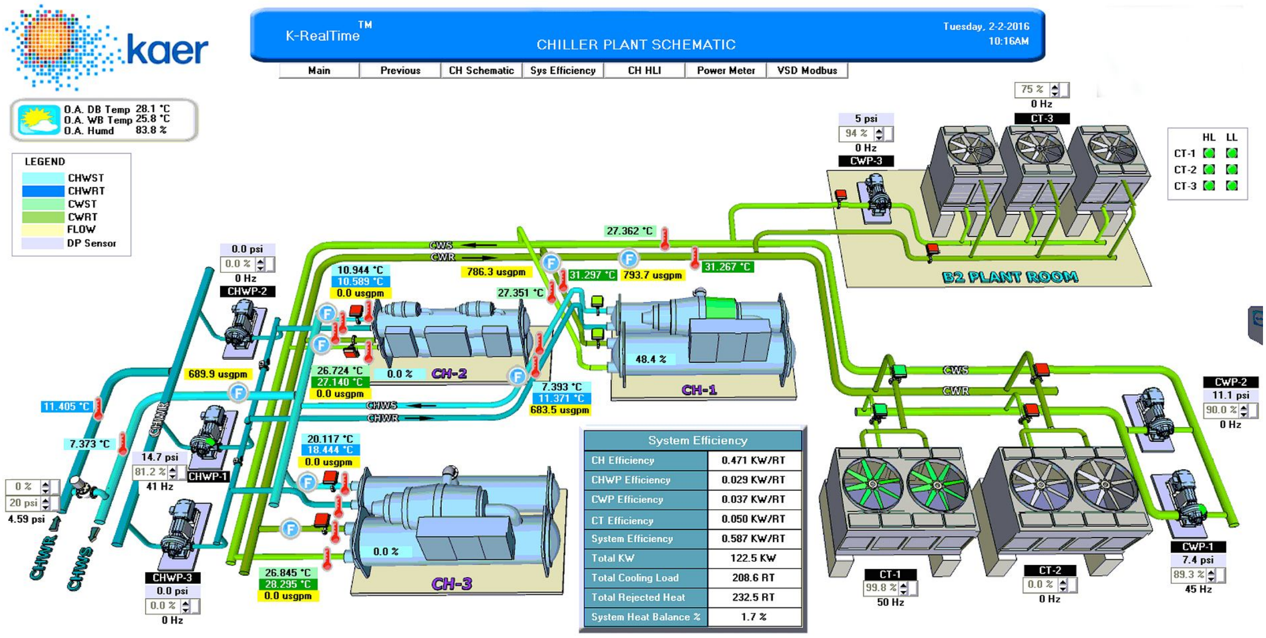

Figure 8. K-RealTime™ air-conditioning & mechanical ventilation (ACMV) controls and optimisation platform uses IoT technology and AI data analytics to make the system more reliable and efficient. Source: (Kaer, 2017)

The reduction in energy use can reach 35% and the financial savings between 10-20% but can be up to 70% in some cases. The optimisation of the system benefits both the user, who pays per cooling unit consumed, and Kaer, who pays for fewer resources per cooling unit.

The equipment technology has not changed considerably, instead the optimisation software, data collection and the way the service is delivered can reduce costs, energy usage and emissions by half (Mackerness, 1999; EMF, 2017b).

2.4. The WikiHouse 4.0 by Architecture Zero Zero and Arup

WikiHouse is an open-source construction system free to download and customize, that enables local manufacture with minimal construction skills through technologies such as 3D printing and CNC cutting.

In 2014 the WikiHouse 4.0 prototype was built as the world first open-source digitally manufactured 2-storey house. Anyone can adapt and assemble it together in a few days for less than £50K. It is mainly made up of flat-packed modular timber components that can be ‘printed’ and assembled together in-situ, minimising transportation costs and emissions. Figures 10 and 11 show how the easy-to-store flat-packed timber components are quickly assembled together to form the building’s skeleton.

Its building services circular features include virtually-controlled plug-and-play lights, sensors and ventilation connected to the house’s Wi-Fi, OpenHAB Building Automation software, a DC Power and Data Network (saving energy and transformer components) and comprises an open-source heat exchanger built from 3D printed parts and aluminium from repurposed drinks cans (The Building Centre, 2014; Arup, 2016b).

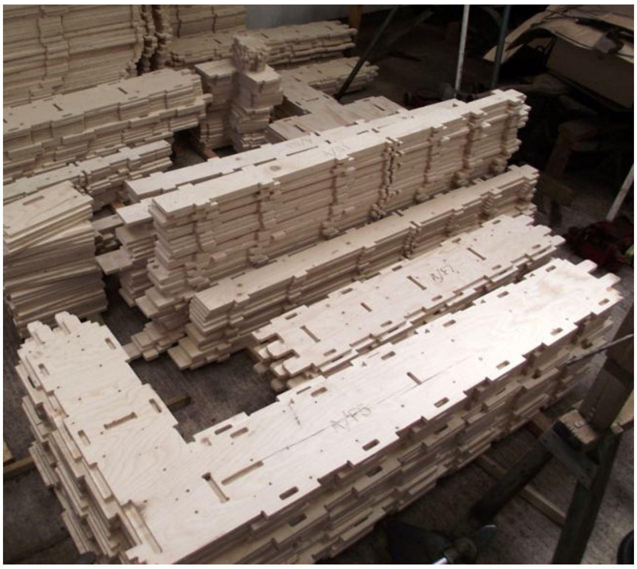


Figure 9 & Figure 10. Flat-packed CNC-cut timber components before and after assembly in the Wikihouse 4.0 prototype. Photography credit: Margaux Carron

2.4.1. New Venlo City Hall by C2C ExpoLAB and Kraaijvanger Architects

Designed using Cradle-to-Cradle® (C2C) certified products where embodied resources are cleanly returned to biological and technological streams after use (Braungart and McDonough, 2018), the building also embeds circular principles on several design fronts: buildings as material banks, design for disassembly, circular procurement and a return-on-investment business model. An ambitious C2C project brief led the design team to an early exploration of the market and engagement with suppliers and experts. This anticipative procurement process became a success, starting with 5 available C2C certified products and ending up convincing more than 30 suppliers to adopt circular processes. All products and materials were selected to be healthy and to be reused or recycled at the end of life.

Another success was the financial model: the investment of €3.4 million in C2C® products was calculated to have a ROI of €16.9 million over 40 years through energy savings, product life cycle costs and an increase in employees' productivity because of indoor air quality enhancements. In addition, a take-back contract was agreed with the furniture suppliers where they would pay €300.000 (18% of the original value) to recover the fittings after 10 years (Baker-Brown, 2017).

2.4.2. Liander headquarters by Rau Architects and Turntoo

As a whole, this is probably the most successful circular building so far. Design strategies include conservation and reuse of 80% of the materials in the previous office building, minimization of material use, and employment of materials that can later continue their biological or technical life cycle. But the main feature is the material passport information registered in Madaster Platform- a public, online cadastre of materials in the built environment, also initiated by Turntoo. The document includes information about the origin of materials, who has handled them, where they were temporarily stored and ways in which they can be repurposed. The online platform is set to become a digital location where real estate assets, BIM models and material passports can be stored for coordination between stakeholders or for individual, secure management. As co-founder Thomas Rau states: "waste is material without an identity" (EMF, 2016; Madaster, 2018).

One of the main drivers for the success of this building was the joint venture contract between the main stakeholders involved. A consortium between VolkerWessels Vastgoed, RAU architects, Innax / HOMIJ and Boele & van Eesteren was created for the delivery, management and (at least) 15 years maintenance of the building. This innovative procurement model aligns designers and suppliers' interests with those of the client, guaranteeing a durable, easy-to-maintain building which is also energy positive.

Homij, the building services contractor, was actively involved in the circularity of the building. They designed digitalised environment controls and plug-&-play components and used their DLS[4] system for the design and installation of this building. The DLS digital library fits within the BIM model of the building ensuring pre-fabrication, standardisation, efficient logistics and complete information transfer from design to facilities management. This facilitates maintenance and increases end of life recovery opportunities by integrating building services information within the building's material passport document (Homij, 2018).

2.5. Drivers and barriers

Although some buildings and suppliers have demonstrated a degree of implementation of CE in building services, it is still marginal. Five main barriers and their counterpart drivers affecting the transition to circularity have been identified in Table 7.

Table 7. Barriers & drivers affecting the transition to circular services. Source: (Arup, 2016b; Mul, Roos and Jutte, 2016)

Barriers	Drivers
Traditionally, services were embedded into the structure and façade of a building, obstructing their upgrade, removal and replacement	Design and install services so that their manipulation does not affect other building layers ('Shearing Layers' concept)
Insufficient quality and quantity of secondary materials and components. Products and systems are not designed for life extension and technology evolves fast, becoming obsolete. Their residual value at the end of use is low, materials are not recyclable, and the secondary materials market is poor	Design for disassembly, market modularity agreements and the creation of virtual secondary markets
No understanding of the financial benefits, circular business models and lack of incentives.	Financial analysis of new business models that favour life extension such as leasing, product as a service or take-back contracts are necessary to unveil the economic benefits and incentives for all stakeholders
Fragmented structure of the industry and value chain: during the life cycle of a building, various works or services are procured separately: contracts for design, construction, maintenance, renovation and demolition are procured independently. The companies executing the various contracts are not in contact with each other. This hinders the alignment of each other's needs and innovation	New partnerships and joint ventures between different parties of the value chain can drive innovation and align interests so that everyone designs for life extension and high utility
No clear articulation/framework for how clients, contractors, suppliers and designers should change the design and procurement process of buildings	Guidelines are needed on how the current process must adapt, what relations and contracts need to be in place and what decisions have be made and when to allow circularity to flourish

[4] DLS: Homij's in-house BIM library of building service components

2.6. Design and procurement of circular building services

This last barrier/driver is the main focus of this paper as there is certainly a knowledge gap around the decision-making process involved in the design and procurement of circular building services.

The RIBA Plan of Work is the most widespread timeline framework in the construction sector, but it is clearly fixed to “linear economy” “cradle-to-grave” type projects: Stages 1-3 (~A-D in the old 2007 framework) represent the first brief and design steps, stage 4 (~E-H) is key for technical design and generally tendering, stages 5-6 (~J-L) are the construction and handover phase and stage 7 is the ‘In Use’ condition and may endure until the building’s end-of-life. Still, the 2013 version, shown schematically in Figure 12, takes three positive steps towards an adequate design and procurement process for circular buildings (RIBA, 2013):

1. The circular display of the 7 stages is a nod to the whole life cycle vision, but the unclear connection between the final ‘In Use’ and the first ‘Strategic Definition’ stages leaves it as an unfinished gesture.
2. The 2007 version established a fixed tender process between stages G-H in line with the traditional procurement route. In contrast to this, the new version suggests more flexibility to engage with contractors and manufacturers, and tender. This opens the door to other procurement routes that are gaining popularity such as ‘design and build’ and management contracts. Given the lack of available circular suppliers and the immaturity of the secondary materials market, this flexibility allows earlier and longer engagement processes that can benefit circularity.
3. Previously, the end of design procurement was set at Stage L ‘Post Practical Completion’, suggesting only some minor post-construction adjustments. The introduction of a final ‘In Use’ Stage 7 in the 2013 version transfers emphasis to a whole life cycle concept of buildings. This highlights for the first time that the responsibility of designers and procurers does not finish upon completion, accounting for in-use aspects such as maintenance, replacement and upgrade.

These are welcome steps but there are still core concept changes needed to advance towards a circular design and procurement stage programme. The whole life cycle approach to buildings is not new but it should be reflected in design timeline frameworks such as the RIBA Plan of Work. Figure 13 gives an overview of how circular procurement should work in any supply chain and what drivers can be used to stimulate that change. It is intentionally located under Figure 12’s RIBA Plan of Work for comparison. The latter contemplates the procurement of design, production, supply and use activities but still misses the reverse logistics needed to close the loop: repair & reuse, repurpose and recycle (Jones, Kinch Sohn and Lysemose, 2017).

Figure 11. RIBA Plan of Work 2013 circular diagram. Adapted from (RIBA, 2013)

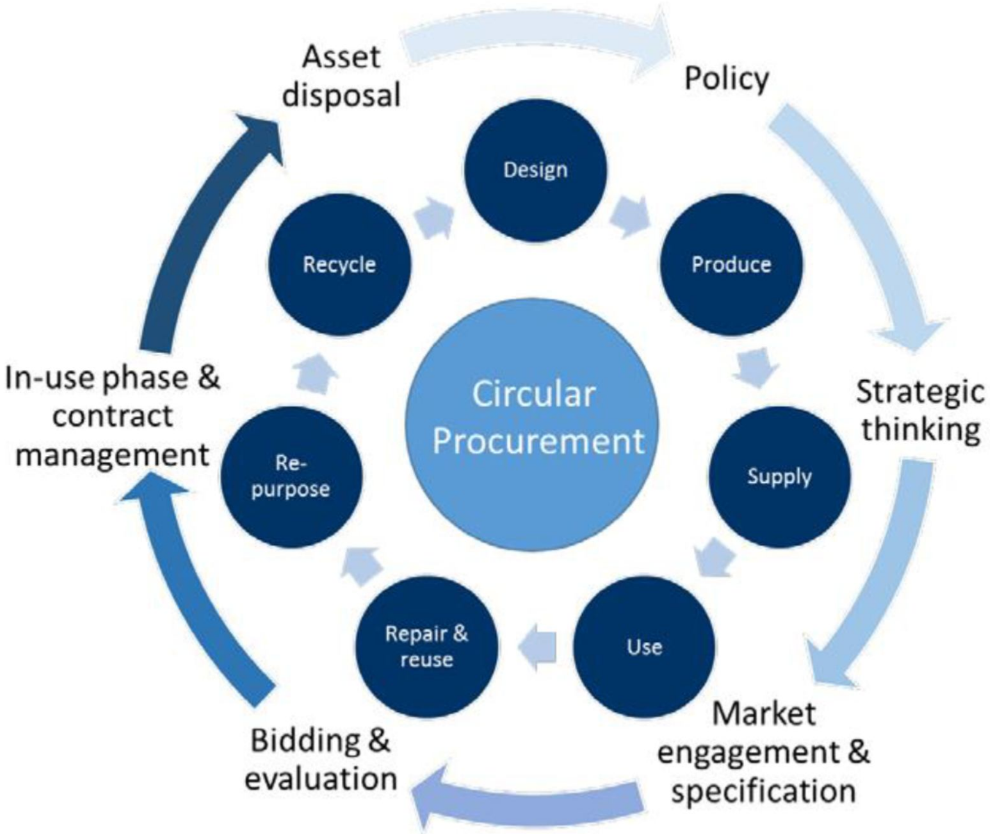

Figure 12. Circular procurement diagram. The inner circle shows the different constituents of the supply chain and the outer circle the drivers needed to integrate them (Jones, Kinch Sohn and Lysemose, 2017)

3. Methodology

Two case study buildings were selected for the project, from which key stakeholders were identified and contacted to interview. It was important to select buildings that allowed easy access to these key stakeholders; for this reason, one from the UCL estate was chosen and one that Arup had designed. Meanwhile, a literature review on the topic was undertaken and background information on the design process of both buildings was gathered through a desk-based survey. The interviews were recorded and transcribed and followed a semi-structured format, aiming to focus on aspects of building services design and decision making in both buildings. Analysis of information gathered from the interviews aimed to identify how to map decision making on to a timeline and to provide more general guidelines for circular procurement of building services. The two case study buildings are presented below.

3.1. Case study 1: 22 Gordon Street (The Bartlett School of Architecture, UCL)

Located within the UCL Bloomsbury campus, this is a refurbishment project of the former Wates House (dated circa 1975) to house the entire Bartlett School of Architecture. The brief started as a small extension with a services and façade upgrade and ended up becoming a complete refurbishment and extension project comprising a net usable area increment of 3,500m^2: from 2,800 to 6,300m^2 (+125%).

Figure 13 & Figure 14. Wates House before and after refurbishment. Photography credits: Matt Clayton and Jack Hobhouse

The building had ambitious sustainability targets as part of UCL's wider programme to modernise its estate, including a corporate Sustainable Building Standard but no specific circular economy targets. Expedition Engineering led the strategy with an expected 30% carbon dioxide reduction on 2010 Building Regulations and the achievement of a 'BREEAM Excellent' rating. Building services designed and commissioned include a full HVAC system, lighting and electrics including a new transformer substation, a fibre connection and server rooms, toilets and plumbing, 2 new lifts and fire-safety services.

The project followed a full 2007 RIBA stages process starting mid-2012 with the building opening at the end of 2016. Adopting a bespoke design and build procurement route, a consultant' design team delivered the project up to Stage D including planning application and the general contractor Gilbert Ash completed design and construction from Stage E onwards. The team was led by UCL Estates (representing the client), coordinated by Mace (the project manager) and delivered by a group of design consultants including architects Hawkins Brown and the M&E engineers Buro Happold. The team structure is presented in Figure 16.

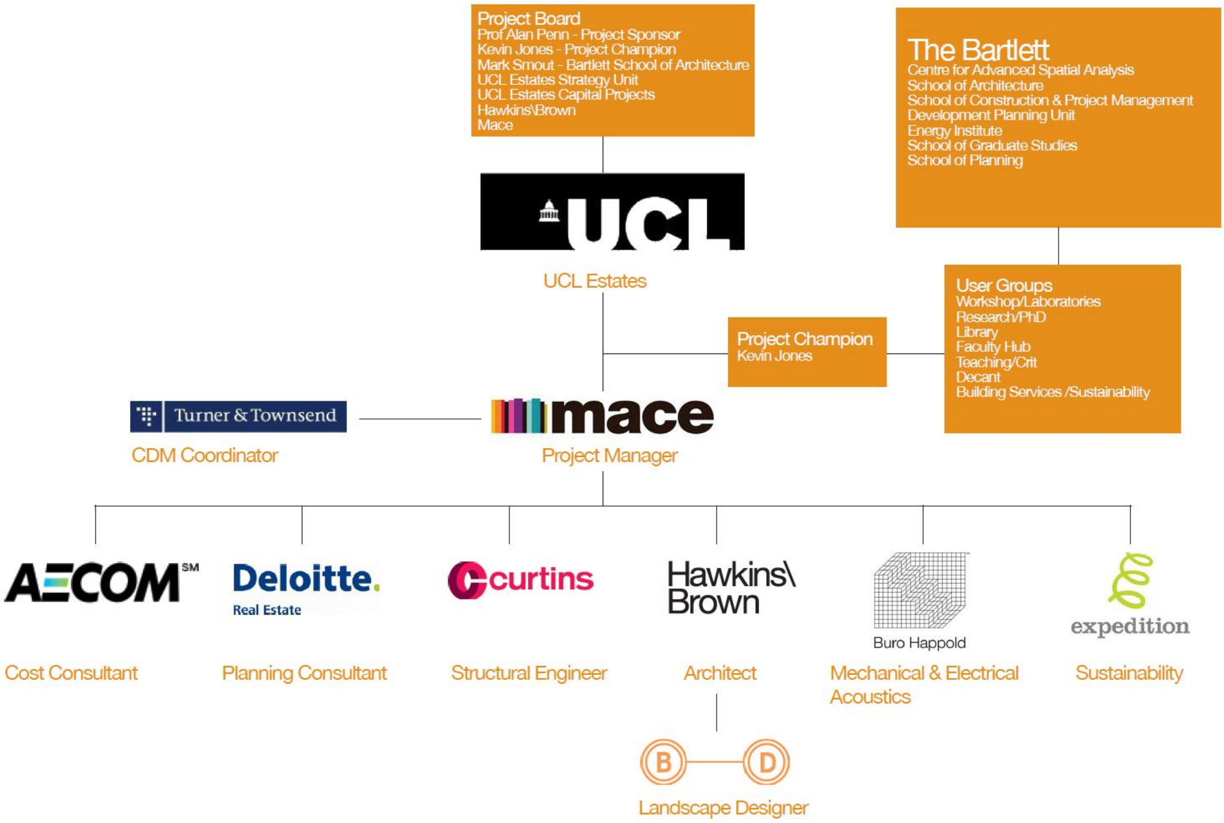

Figure 15. 22 Gordon Street design team structure. Source: Stage D report (Hawkins Brown, 2014b)

3.2. Case study 2: The Circular Building

Built as a temporary showcase building, The Circular building was a collaboration between Arup, Frener & Reifer, BAM and the Built Environment Trust. The building stood a month in The Building Centre's courtyard during the 2016 London Design Festival. Its objective was to test and show the industry how to design a generic building with circular strategies. Moreover, it wanted to demonstrate that this was only possible through a collaboration between designers, contractors and product suppliers. It was designed in 6 months (April-September 2016) and built and dismantled in a month: (September-October).

The building was mainly a container, but it was lightly serviced by an HVAC system, an AC connection to The Building Centre, PV panels, a battery feeding DC power and lighting.


Figure 16 & Figure 17. The Circular Building outside and inside. Photography credit: Arup

3.3. Interviews

A semi-structured approach to interviews was taken, with a list of key broad topics made to ensure maximum opportunity to gather relevant and useful information without restricting interviewees to fixed responses. Six approximately 1-hour interviews were carried out with design team members that influenced the decisions of both projects. Summary data for each interview including participants' name, initials and position is shown in Table 8.

Table 8. Interviews summary data

Project	Interview	Interviewees	Position in project	Interviewers	Date	Location
22 Gordon Street	**1**	**Ben Stubbs (BS)** **Marc Smout (MS)**	UCL Estates - Sustainability team Client design champion	Dr Ben Croxford (BC) Dr Dimitrios Rovas (DR) Simon-Joe Portal (SP)	13-04-2018	UCL Central House
	2	**Kevin Jones (KJ)**	FM of The Bartlett & client (UCL) users design champion	Dr Ben Croxford (BC) Dr Dimitrios Rovas (DR) Simon-Joe Portal (SP) Ramon Mendoza (RM)	03-05-2018	22 Gordon Street
	3	**Kenichi Hamada (KH)**	Mechanical engineer at Buro Happold	Dr Ben Croxford (BC) Ramon Mendoza (RM)	01-06-2018	Buro Happold's
	4	**Tom Noonan (TN)**	Project architect at Hawkins Brown & later seconded to Gilbert Ash	Dr Ben Croxford (BC) Ramon Mendoza (RM)	26-06-2018	22 Gordon Street
The Circular Building	**5**	**Rachel Athis (RA)** **Carolina Bartram (CB)**	Architect at Arup Structural engineer at Arup	Simon-Joe Portal (SP) Ramon Mendoza (RM)	14-06-2018	Arup's office
	6	**Richard Boyd (RB)**	Materials consultant with expertise in CE	Simon-Joe Portal (SP) Ramon Mendoza (RM)	28-08-2018	Arup's office

During the 22 Gordon Street interviews, questions were asked to understand the decision-making process around the brief, the general design of the building and on specific building services including HVAC systems, electrics and lighting, plumbing and toilets, fire, lifts, and any specialty machinery. For The Circular Building, questions were asked to understand the circular brief, the strategies and products used, particularly for building services, the design and procurement of circular components, relationship with suppliers, and problems and successes encountered. The full list of questions can be seen in the Appendix section.

During the interview, notes were taken and the conversation was recorded using a Livescribe 3 Smartpen (Livescribe, 2017). Audio files were then used by the researcher to transcribe key information that was then structured by project and topic as seen in Table 9. A desk-based survey on available design documents complemented this information and helped identify when decisions became finalized within this process.

Table 9. Key information gathered, and supplementary documents used

<table>
<tr><th>Project</th><th colspan="4">Topics</th><th>Supplementary documents</th></tr>
<tr><td>22 Gordon Street</td><td rowspan="2">Project timeline and milestones</td><td colspan="2">Key decision-making processes:
- General
- Building services-specific</td><td>Key decision-makers and their motivations</td><td>- UCL Bloomsbury Masterplan (Lifschutz Davidson Sandilands, 2011)
- Design Brief (Hawkins Brown, 2013a)
- Stage C Report (Hawkins Brown, 2013b)
- Stage D Report (Hawkins Brown, 2014b)
- DAS Report (Hawkins Brown, 2014a)</td></tr>
<tr><td>The Circular Building</td><td>Circular strategies/ levers</td><td>Circular MEP components/ products</td><td>Barriers, questions & findings</td><td>http://circularbuilding.arup.com/
(Arup, 2016a)</td></tr>
</table>

4. Findings from interviews

The information in this section is partially taken from interviews, in some cases these are direct quotes and assigned to the person who made them, in others they are paraphrased for clarity.

4.1. 22 Gordon Street

4.1.1. Overview of the decision-making process

Although the project design was staged during the transition between the 2007 and 2013 RIBA Plan of Work, the former plan has been used to frame the process. The diagram in Figure 19 gives a general overview of the decision-making process as a system. This includes the decision makers (‘*who*’), the RIBA stages that framed the process (‘*when*’), the decision categories analysed (‘*what*’) and the motivations (‘*why*’).

Figure 18. Overview diagram of the decision-making process of 22 Gordon Street. Adapted from (RIBA, 2013)
*Speech bubble tails are not precise or exclusive. They indicate when the connection was more intense

The key decision-makers affecting building services selection and specification can be divided in 4 groups:

- A strong client (UCL), structured as a “triangle between UCL Estates, Architecture and the users (represented by the facilities manager: Kevin Jones)” (MS).
- The design team including the architects Hawkins/Brown (TN & team), the sustainability consultants Expedition Engineering and the M&E and fire engineers Buro Happold (KH & team).
- The contractors Gilbert Ash and in particular the M&E contractors Vaughan Engineering.
- The planning authority: the London Borough of Camden and its planning officers.

Each group’s influence varied in intensity over the different stages of the project. UCL Estates took the initial decision at Stage 0 of incorporating the refurbishment of the Wates House Building as part of the strategic Bloomsbury Masterplan. Along with the BSA and users’ representatives, the client (UCL) had its major impact during the early stages, defining the brief in Stage 1 and influencing the design through stages 2 and 3. UCL ISD (Information Services Division) and EM&I (Engineering, Maintenance & Infrastructure) provided key services requirements and specifications through stages 3 and 4. The design team, led by Hawkins/Brown, had a big influence over the development of the brief and general design strategy from stages 1 to 4 at which point the design responsibility was transferred to the contractors Gilbert Ash who took the project to completion from stages 4 to 6. On the specific design and specification of building services, Buro Happold led the conversations from stage 2 to 4 with the influence of Expedition Engineering on the sustainability aspects. Likewise to the architecture, the services responsibility was transferred during stage 4 to the M&E contractors Vaughan Engineering. The London Borough of Camden’ planning officers influenced the project’s brief through planning requirements and the early design through pre-application meetings from stage 2 to planning application at the end of stage 3. Looking back, “the project would have benefited from a leading person that could bring together and realise all the different scattered conversations.” (MS)

Acting as the core of the diagram, the decisions (‘*what*’) and the motivations (‘*why*’) are the most important findings. In addition to specific building services decisions, the ‘brief and procurement’ and ‘general design strategy’ decisions indirectly influenced the selection of MEP systems. Finally, motivations represent ‘*why*’ each party influenced each decision in a certain direction.

To give a sense of context, the timeline in Figure 20 aligns key project milestones with the RIBA stages. The total length of the project is five years from 2011’s UCL Bloomsbury Masterplan to completion at the end of 2016. It is important to note how the project was delayed more than originally programmed due to the change of brief (‘*Enhanced project scope’*) at the start of Stage 3. This explains why this stage lasted more than one year as, in reality, it involved a jump back to Stage 1.

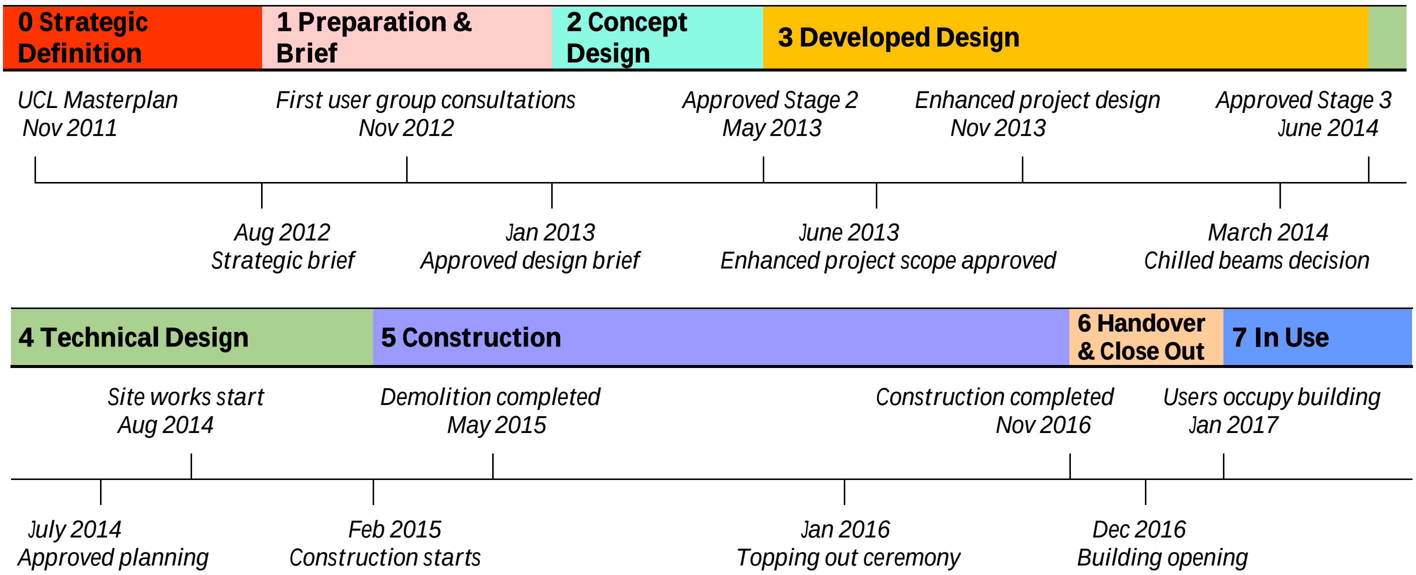

Figure 19. 22 Gordon Street project timeline with key milestones
*Timeline is not precisely to scale, but stage lengths are indicative of their duration

To understand the process in depth, specific decision processes leading to the selection of building services are studied as causal maps in Figures 21-29. Most of the decisions and events identified correspond to the early design stages as it is here when they can impact most strongly on the circularity of the project. These must be read in conjunction with the matrix in Table 10, where the same decisions are matched with key decision-makers influencing them and, most importantly, their motivations. Seen together, the two representations aim to show a 360^{o} picture of the decision process involved in the design of 22 Gordon Street's building services.

Three key general decisions affected building services and circularity: the retention of the concrete frame, the evolution of the brief (Figure 21) and the space planning requirements (Figure 22). The decision to retain the concrete frame (taken early in Stage 1) was the most circular and 'carbon-positive' decision for the whole project but had its consequential design constraints.

Brief evolution

The project's original brief was a modest upgrade of services to the existing building, new toilets, double glazing and a modest 2 storey extension. This was subsequently expanded: It started being "a £300,000 job to fix the windows, and then it went up to £14 and £37 million" for a full refurbishment (MS).

Early-mid 2013 it was questioned if the brief would give the client a decent return on investment and solve the problem, and Hawkins Brown said that it would not. The original project cost was not proportional to the value it was adding: "It costed £7-8 million and no extra area was being added" (KH). The dean, Alan Penn, was very keen on getting a larger floor area, more students and changing the old building's compartmentalised layout with open and adaptable space (see Table 10). The change of brief was approved by the project board in June 2013. This had great implications for all building services strategies. The HVAC solution went from decentralised MVHR units integrated into cladding panels to a centralised AHU located on the roof with local multi-purpose chilled beam units. The power strategy went from keeping the existing external shared transformer to installing a new one. Some existing pipework was being retained before the brief change, but it was completely stripped out and replaced after the upgrade. With the extended project, new occupancy numbers were expected to lead to lift overload and long waiting times. Finally, the fire strategy was greatly affected, considerably increasing the scope of fire-safety services.

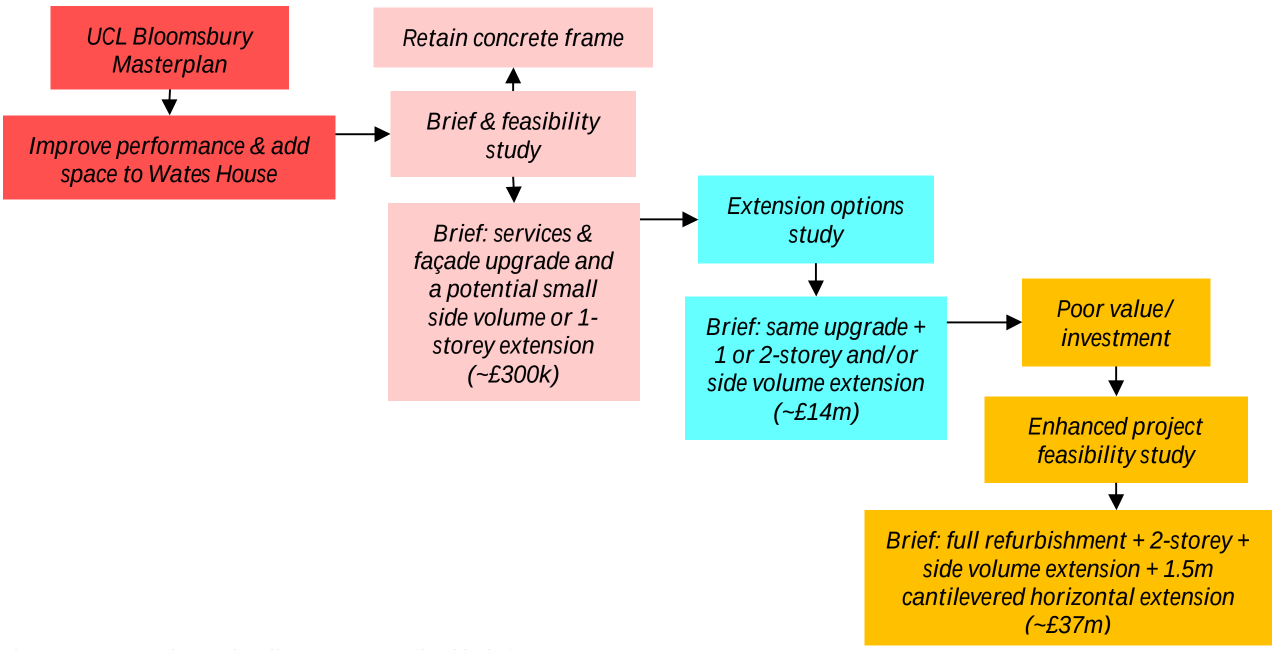

Figure 20. Causal map leading to 22GS's final brief.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages **0**, **1**, **2**, & **3**).

Space requirements and layout evolution

The project champion's experience as a facilities manager, and the BSA representative's insistence, led to two highly circular decisions: designing shared offices to increase occupancy rates, improving the use of the building, and preferring un-programmed, open and adaptable spaces, anticipating a level of flexibility and adaptation, again aiming to maximise the use of the space (see Figure 22 and Table 10).

To maximise the usability of the building, they created a brief with 16-people studio spaces and big 2-people offices that could vary from 2 occupants in winter to 5-6 in summer. "This makes the building a lot more usable… there is nothing less sustainable than an underused building" (MS). Overall utilisation of academic office space in the Bloomsbury campus is low: 33% (~1.5 days a week) (Marmot, 2010), so making people share offices can double this figure. Although this is true in absolute figures, it was discovered on the same study that utilisation rates decrease as the number of people using the office increases. Some space in the building was allocated for future increase of occupancy and 3rd party occupants as part of Bartlett's business model. "These were occupied sooner than expected" (KJ).

The specific nature of architecture teaching and the space planning process also had important effects on the selection of building services. Architecture teaching has the peculiarity of requiring large areas of densely occupied studio space, often under-occupied office space and un-programmed grey spaces. These un-programmed spaces are used for social encounters, 'crit' sessions, team working, exhibitions and fabrication. UCL Estates was not convinced, so the design team decided to design extensive stair landing "grey" spaces that could be used partly as lobbies to comply with fire regulations and for polyvalent and spontaneous uses. These spaces are now being successfully being used. "It was my ambition to make as many grey spaces in that building as possible" (MS). This in turn meant the selection of the air conditioning solution and the user-control strategy would have to satisfy all three different space types.

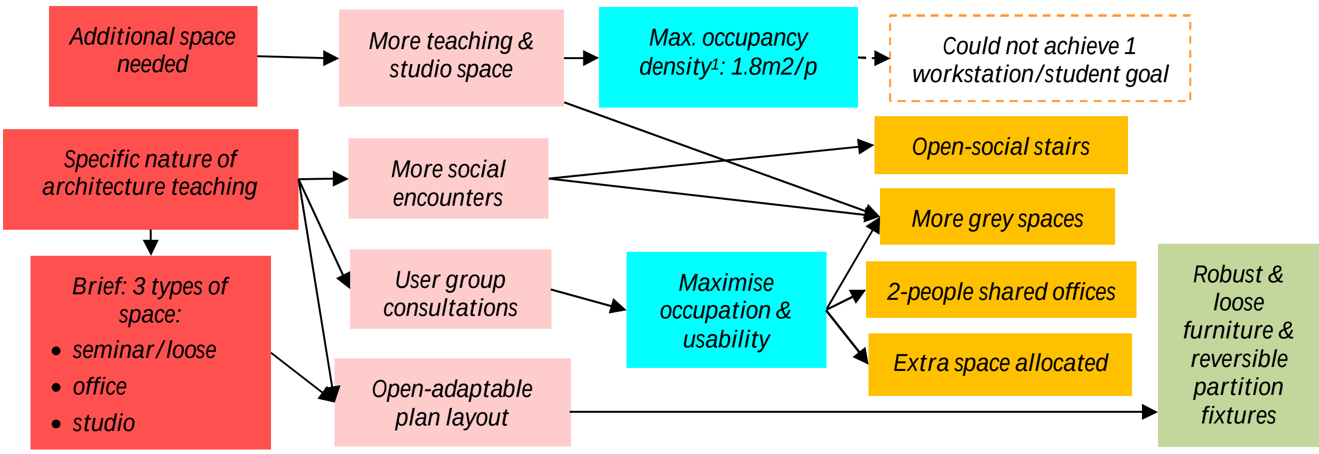

Figure 21. Causal map leading to 22GS's spatial layout decisions.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2, 3 & 4).
*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused.
[1] Occupancy density limit given by maximum cooling load established by Buro Happold

User control strategy over building's air conditioning

The biggest discussions the design team had around building services was about user control (Figure 23). There was a fundamental discussion on how they wanted the building to operate. Very early on, in Stage 1, exclusive natural ventilation was discarded given the high-density occupancies and the decision to connect to UCL's district heating was taken. From that point until Stage 3 it was discussed whether to completely seal the building or run a mix-mode ventilation strategy attending to cost, energy efficiency, sustainability and user comfort: "[UCL] Estates were pushing for sealing it and we [the Bartlett] were pushing for the adaptability of it" (MS) (see Table 10).

It was finally decided that different user-control override mechanisms would be designed for the offices (simple window interlocks) than for the studios (a 'traffic light' indicator would be used to show when the conditions are optimal for natural ventilation).

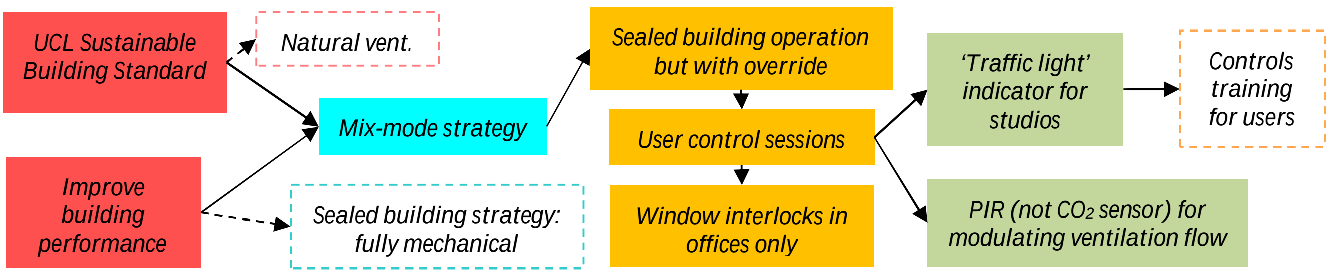

Figure 22. Causal map leading to the selection of 22GS's user control strategy over the building's air conditioning.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2, 3, 4, & 6).
*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused.

HVAC system selection

As previously mentioned, the enhanced project brief triggered the selection of a centralised AHU system for three main reasons: higher budget, the opportunity to open new risers through the slabs and the availability of plant space on the roof given the addition of two new storeys. A decision was taken to avoid perimeter heating to maximise space: 2 extra seats could be gained near the windows. But the problem was not the heating, but the volumes of air required and cooling demand. "The question asked at that time was: How can we manage the 3 type of spaces we have got? The loose-fit spaces such as the seminar rooms with varying occupancies, offices with low density (2-3 people), and the open plan studio spaces" (KJ). Moreover, the constrained floor-to-ceiling heights caused by the retention of the concrete frame led to the selection of multi-purpose chilled beam units that could handle high cooling loads and provide lighting, sensors and fire detection services within it. This was decided around March 2014 (see Figure 24).

To deal with the different space and user types, a positively circular decision was to locate the same standard unit in every different space type and modulate the varying ventilation flows through a PIR sensor and the centralised BMS. Buro Happold pushed for CO_2 sensors but UCL Estates Facilities and Infrastructure team (EM&I) decided against it due to negative experience (see Table 10). After a tender process involving 3 manufacturers, the Stella Flaktwood chilled beam units were selected (FlaktGroup, 2018b). The devices' function works fine, but the IPSUM BMI system (FlaktGroup, 2018a) embedded in them does not communicate well with UCL's centralized Schneider EcoStruxure™ Building Operation software (Schneider, 2018) and it required further commissioning.

The design team wanted to limit, as far as possible, the need for mechanical ventilation and cooling. Initially, "the intention was getting free ventilation and potential night time cooling, however the building works long hours and 7 days a week" (KJ). Buro Happold is currently reviewing the possibility to provide BMS scheduled seasonal night ventilation as part of a seasonal commissioning review.

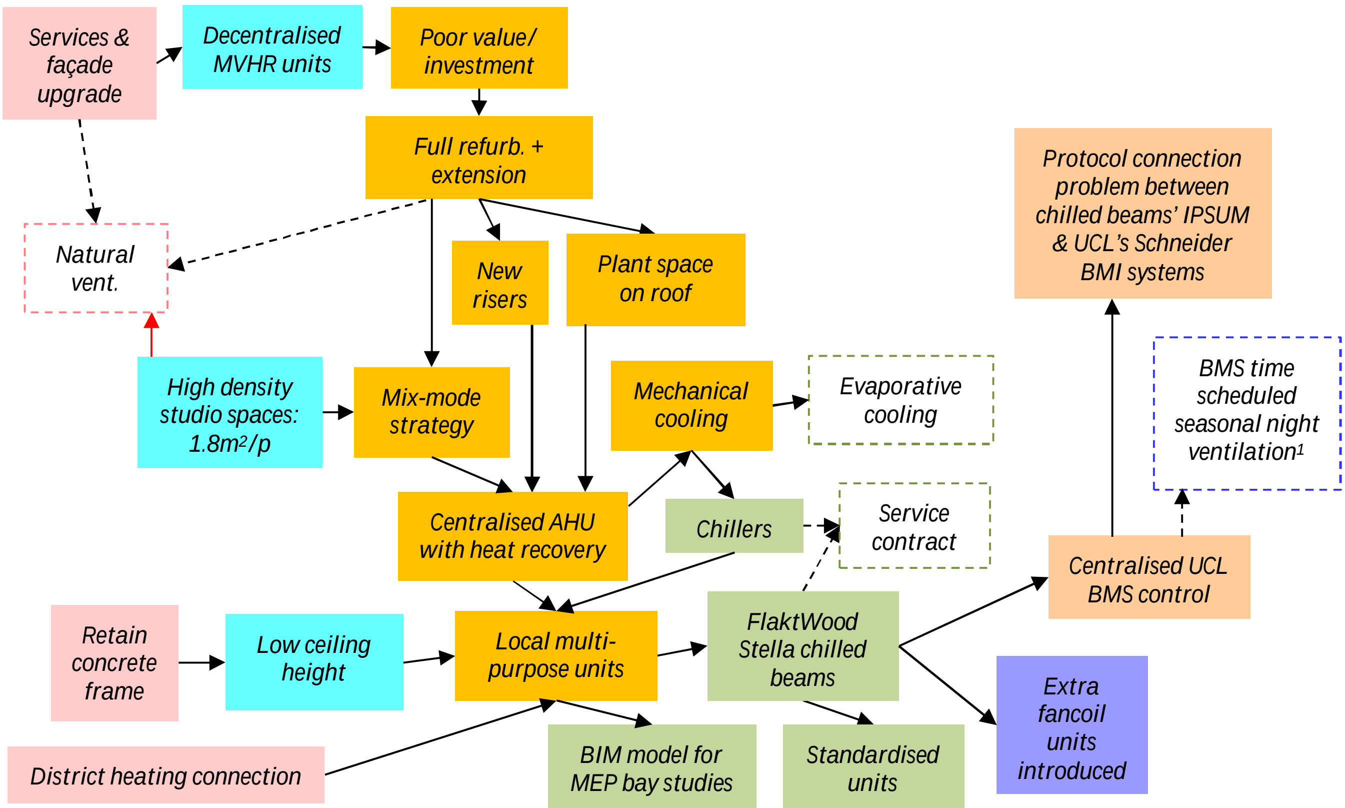

Figure 23. Causal map leading to the selection of 22GS's HVAC system and local multi-purpose chilled beam units.

*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 1, 2, 3, 4, 5, 6 & 7).

*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused.

[1]Night time ventilation is currently not provided but possible via BMS time schedule, and has been recommended as part of Buro Happold's seasonal commissioning review

UCL's EM&I team suggested at Stage 3 an extended 2-3 years servicing plan for the chilled beams and roof chillers in line with a 'soft landings' approach (see Table 10). This circular initiative was discarded for two reasons: neither UCL Estates nor the manufacturers wanted to assume the risk (cost, fear, manufacturer going out of business, contractual liabilities…) and the responsibility around the conflict that would arise between the correct functioning of the serviced devices and UCL's centralised district heating and BMS. "[UCL] Estates is all about risk [management], so you end up going to what you know that works" (BS).

Further on, during construction, the contractors Vaughan Engineers decided to locate some fan coil units where the chilled beams were not able to deal with the load, for example at the top of the atrium stairs.

Power solution (new transformer)

Prior to the enhanced brief, it was estimated that the existing external transformer could cope with the new power load, but the increase in services, area and occupancy led to the decision by UCL's EM&I and Buro Happold of acquiring a new high voltage transformer located in a new basement substation (Figure 25). The capacity of this new transformer exceeds the building's needs, leaving room for future flexibility & expansion, thus increasing circularity. A new fibre connection was also introduced from the Chemistry building with internal distribution done through ISD server rooms located at each level.

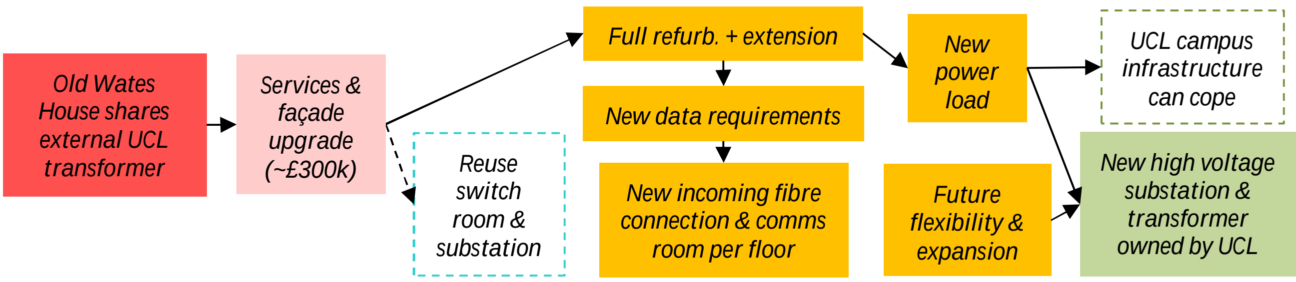

Figure 24. Causal map leading to the decision of installing a new transformer at 22GS.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2, 3 & 4).
*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused.

Lighting solution

The lighting strategy (Figure 26) was straightforward. UCL's Sustainable Building Standard and the environmentally conscious design team pushed for replacing the old lighting system with new efficient LEDs. Internal height constraints and the HVAC solution generated the opportunity to integrate the LED luminaires into the FlaktWoods Stella chilled beams.

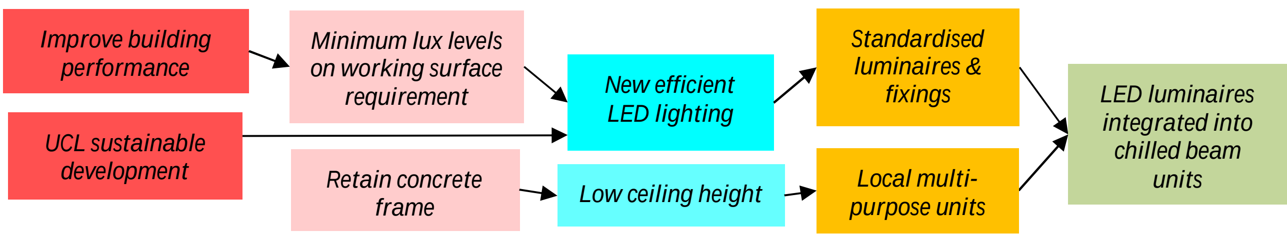

Figure 25. Causal map leading to the decision to integrate LED lighting into the local multi-purpose units at 22GS.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2, 3 & 4).

Plumbing solutions (pipework, toilets and DHW)

Decisions taken around the toilet strategy were particularly circular (Figure 27). Influenced by the input of the facilities manager (KJ), toilet components and fixings were specified to be high-quality, and given UCL's forward strategic thinking, they were designed as equally-sized, gender-neutral toilet cabins. "Money spent on quality toilets is actually money really well spent" (KJ). In a densely occupied building they break often and need a lot of maintenance.

A new centralised DHW was installed to provide hot water to the basement and ground floor changing room showers. This solution avoids the need for water storage, saving embodied carbon in comparison to a decentralised solution, but heat circuit losses could lead to savings being offset by a higher operational carbon footprint. A further LCA would be necessary.

Buro Happold specified a range of materials for plumbing from their internal guidelines (based on BS and CIBSE) from which the contractor chose. They do not include any circular criteria at present.

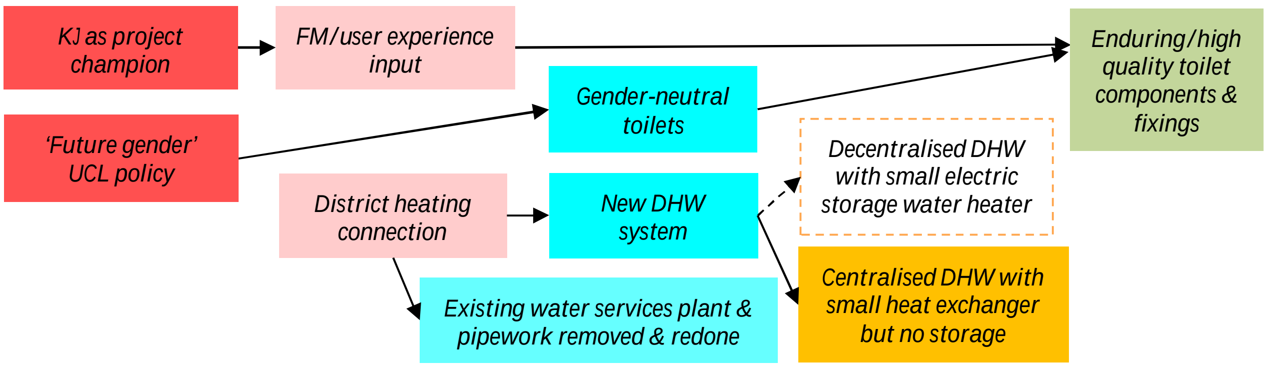

Figure 26. Causal map leading to plumbing decisions including pipework, toilets and DHW system at 22GS.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2, 3 & 4).
*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused

Fire engineering solution

Fire engineering services were greatly influenced by the enhanced brief regarding two decisions: The vertical extension of the building from 6 to 8 storeys meant the last evacuation floor was above 18m from the ground floor and a fire-dedicated core was required, and the introduction of the atrium stairs meant that a 'fire-engineered' solution was needed to solve this fire hazard. Sprinklers were avoided thanks to escape distances being under 18m in length (HM Government, 2009). See Figure 29.

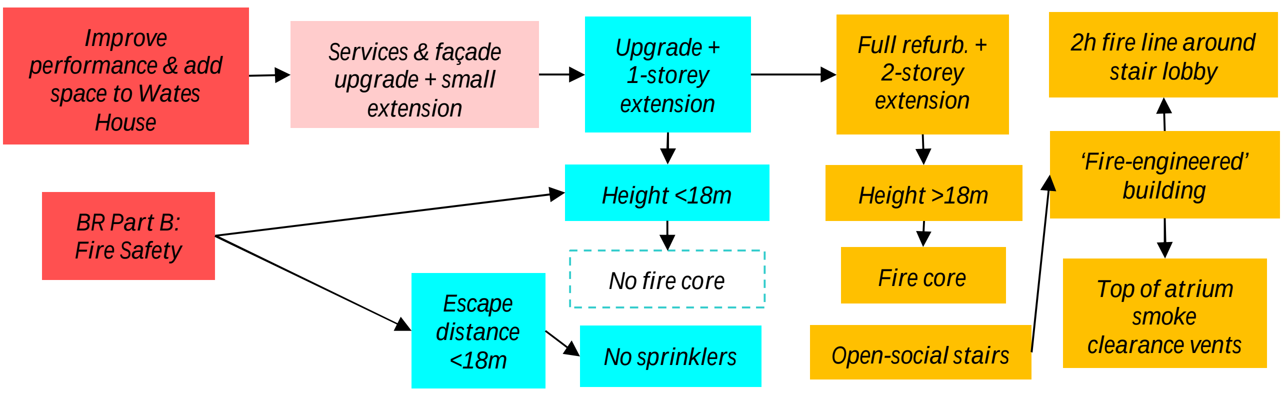

Figure 27. Causal map leading to fire engineering decisions including the fire core and the 'fire-engineered' atrium at 22GS.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2 & 3).
*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused

Vertical transportation solution

The retention of the concrete frame was the biggest driver for transportation strategy decision to fit no more lifts than the two existing. An extra lift could not be placed on the façade due to conservation area restrictions, or internally due to retained structure constraints. The addition of the atrium stairs, supported by the architects and The Bartlett, was meant to relieve this under-provision and encourage fitness and social encounters: “It was a conscious decision [not to put enough lifts], both because of the cost of putting in an extra one, and because we were right on the limit of needing one” (MS).

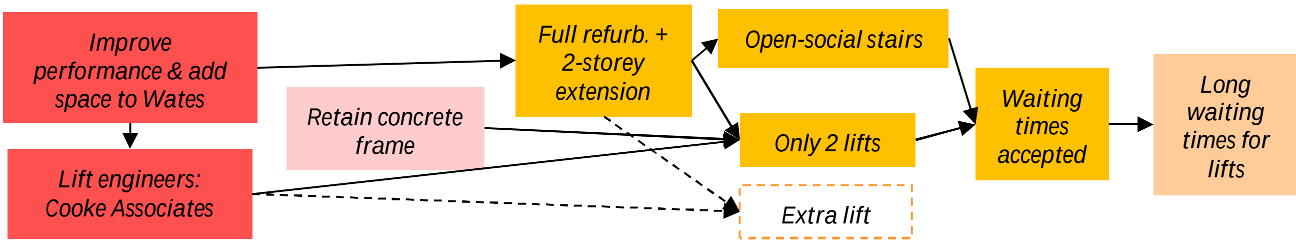

Figure 28. Causal map leading to the decision of not installing an extra lift at 22GS.
*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 3, & 6).
*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused.

Key decision-makers influencing decisions

Table 10 matches all discussed decisions with key decision-makers influencing them and their motivations.

Table 10. Matrix crossing key decisions with decision-makers and their motivations at 22GS (‘what’ vs. ‘who’ & ‘why’). To be read in conjunction with figures 22-30

Key final decisions	Client (UCL): Project sponsor (AP)	Client (UCL): Project champion (KJ)	Client (UCL): BSA rep. (MS)	Client (UCL): UCL Estates (BS & team)	Client (UCL): UCL ISD & EM&I	LB Camden: Planning officers	Hawkins/Brown: TN & team	Buro Happold: KH & team	Expedition: Team	Vaughan: Team
Brief evolution										
·Improve performance & add space to Yates House	BSA needs: more teaching and studio space needed			Bloomsbury Masterplan						
·Brief evolution from £300k to £37m full refurb. + extension	More space & students			Poor value/ investment		Pushed for high ambitions	More invest. to achieve brief			
Space design and requirements										
·User group consultations	User experience input on design						Understand needs			
·Open-adaptable plan layout	Nature of arch. teaching. Increase usability									
·Open-social stairs	Enjoyable, social & fit experience						Arch. feature			
·More unique/grey space - compromise workstations			More crit & social spaces	Challenged decision			More arch. unique spaces			
·2-people shared office	Increase occupation rate/utilisation									
·Achieve 1 workstation/student	Initial goal							Max. occupancy density: 1.8m2/p		
·Robust & loose furniture & reversible partition fixtures	Nature of arch. teaching	Support heavy-duty	Adaptability						Future adaptability	
User control strategy over building’s air conditioning										
·Mix-mode strategy		User-control/ adaptability						Allow mid-season natural vent. - reduce emissions		
·Sealed building strategy: fully mechanical				No wasted energy						
·Window interlocks in offices & 'traffic lights' indicator for studios		'Traffic lights' idea			Limit interlocks to offices			Mech. system off if open window	Reduce 'perform. gap'	
·PIR (not CO2 sensor) for modulating vent. flow					CO_2 sensors negative exper.			Flow control	Reduce emissions	
·Controls training for users		Ensure correct use							Reduce 'perform. gap'	

Key final decisions	Decision-makers: Client (UCL)					LB Camden	Hawkins/Brown	Buro Happold	Expedition	
	Project sponsor (AP)	Project champion (KJ)	BSA rep. (MS)	UCL Estates	UCL ISD & EM&I	Planning officers	TN & team	KH & team	Team	
HVAC system solution										
·Retain concrete frame				Emb. carbon & cost					Emb. carbon	
·Expose concrete frame							Aesthetics/ head height	Thermal mass/ head height	Thermal mass	
·District heating connection				UCL standard req. - efficiency improvements planned		Planning requirement			Worry about DH's effic.	
·Centralised AHU with heat recovery				+ efficient; - cost				Plant space on roof. More efficient - less embodied		
·Local multi-purpose units		Manage different space types					Head height	High C/vent. load		
·Flakt Woods Stella chilled beams							Aesthetics	Performance		
·Standardised units					Maintenance/ replacement				Design waste out	
·Service contract for chillers/chilled beams				Economic risk	Soft landing integration					
·BIM model for MEP bay studies										Coordin.
·Extra fancoil units introduced (eg: top of atrium stairs)										CBs insuff: high C load
·Centralised UCL BMS control					Monitor perform.			Monitor perform.		
Power solution (new transformer)										
·New high voltage sub-station & transformer					New elec. load & future flex.			New elec. load & future flex.		
·New incoming fibre connection & comms room per floor					New data requirements			New data requirements		
Lighting solution										
Minimum lux levels on tables requirement				UCL standard						
·Standardised luminaires & fixings					Minimise spares			Minimise spares		
·LED luminaires integrated into chilled beam units							Head height	Available/ integration		
Plumbing solutions (pipework, toilets and DHW)										
·Gender-neutral toilets				'Future gender' UCL policy						
·Existing water service plant & pipework removed & redone								Upgrade needed/ water efficiency		
·Decentralised DHW with electric storage water heater								More efficient: reduce heat loss		
·Centralised DHW with small heat exchanger but no storage				District heating connection			Lack of plant space?			
·Enduring/high quality toilet components & fixings		Worth the investment								
Fire engineering solution										
·No sprinklers required						Escape dist <18m		Escape dist <18m		
·Fire-fighting core required						New top floor height >18m		New top floor height >18m		
·'Fire engineered' building: 2h fire line around stair lobby	'Social' stairs layout decision					Open stairs: fire spread risk	'Social' stairs layout decision			
·Top of atrium smoke clearance vents						Smoke spread				
Lifts										
·Only 2 lifts - long waiting times accepted			Encourage use of stairs	long waiting times accepted		No external lift: conserv. area	Retained struct. constraints			

*Decisions are colour coded as per the RIBA stage they were finalised in (Stages 0, 1, 2, 3, 4, 5 & 6).

*Filled boxes represent decisions taken and dotted-line boxes decisions considered but refused.

4.2. The Circular Building

4.2.1. Overview of the process, circular concepts and strategies

The design and procurement process of this project was less linear and structured than 22 Gordon Street given the conditions: short time, temporary nature of the building, improvisation involved, and novelty and unpredictability of designing and procuring a circular building. For this reason, the analysis of this project is not based on the process and its stakeholders but on the strategies and concepts applied, their level of success and the findings that can be extracted from the experience.

Based on interview conversations and the literature review, the diagram in Figure 30 attempts to picture the vision behind The Circular Building, which is heavily driven by Arup's '7S Model' and Ellen MacArthur's ReSOLVE framework (EMF, 2015; Arup, 2016b).

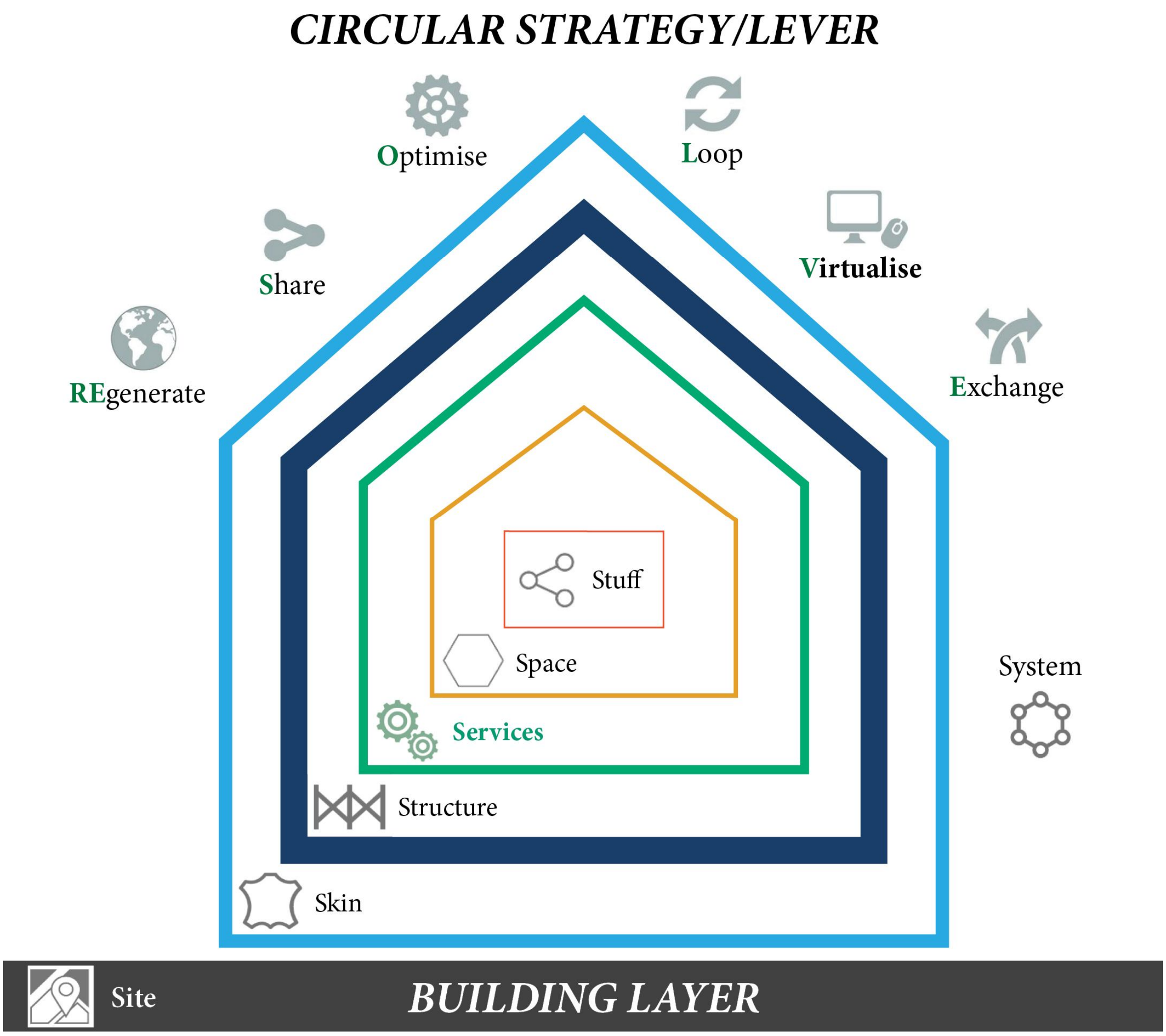

Figure 29. Overview diagram of the circular concept and strategies behind The Circular Building.
Based on the '*shearing layers*' and the *circular levers* concept (EMF, 2015; Arup, 2016b)

As seen in Figure 31's timeline, the building was designed, procured and erected in five months: from April 2016 to the start of the London Design Festival on the 17th of September 2016. Conversations on the brief and design sessions occupied approximately half of the process, leaving less than three months for approaching suppliers, design and finally construction. It is important to note that suppliers were appointed throughout the process in an improvised ongoing procedure. The building was dismantled after the exhibition and some products were returned to suppliers as part of a take-back agreement while other products were reused by Arup.

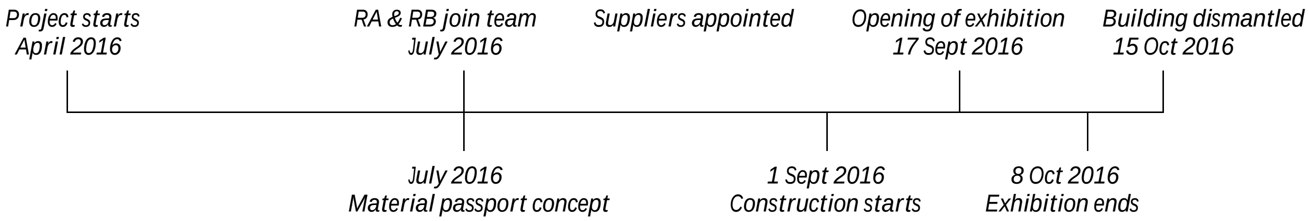

Figure 30. Timeline for The Circular Building project

The project brief mainly focused on the following circular concepts/strategies:

- Flexible space: Based on the 7S ‘shearing layers’ concept and inspired by Japanese houses.
- Flexible services: Arup is presently developing plug-and-play electric circuits, appliances including sensors and lighting, and desk bays to increase flexibility and avoid rigid wall-embedded systems.
- Low energy consumption strategies: Insulated cassette cladding panels developed with Accoya timber manufacturers (Accoya, 2018), natural ventilation, saline aqueous battery, low energy lighting and PV panels. (Note the PV’s did not work in this location because they were overshadowed in the courtyard, but the building was designed to be replicated as a low energy, bigger building).
- Design for deconstruction: Using mechanical and push-fit connections instead of chemical/welded connections. Maximise off-site fabrication and avoid wet-trade construction.
- Materiality and information: Material or element traceability (material passport) to allow product/ material loops. For this, digital technology is essential and was applied in the project through BIM modelling in Revit (Autodesk, 2018) and the project’s website: *circularbuilding.arup.com*. The enterprise proved a success in many ways, but interviewees regretted some missing information, and archiving data using several formats instead of using an integrated BIM model (see Table 11). Services were the most difficult on this front: with difficult to trace components and limited return of materials. E.g. Electrical cables are sustainable or toxic?

Different strategies were applied to each building component and their procurement experienced different barriers and levels of success. Table 11 summarises these by matching building layers with ReSOLVE levers. At a system/general level the main regrets were: the vagueness of the brief and the lack of time (management) as this deprived the designers from developing an effective approach to the supply chain and consequently, they had to design to what was available in the market, (rather than designing new products).

The structure was the first component to be sourced: recovered steel beams were used to give a sense of commercial appearance and their sizes dictated the shape of the building.

According to Arup (RA and CB) the most challenging but successful building component was the Accoya timber façade. The envelope was designed with flat-packed CNC-cut boards made of sustainably sourced wood treated without any toxic substances to endure all weather conditions. Moreover, the boards were integrated into the structure through Lindapter Girder clamp connections (Lindapter, 2017) to avoid welding and drilling, and the waterproofing layer was made without toxic petrochemical materials.

Table 11. TCB's circular strategies: successes and regrets. Source: http://circularbuilding.arup.com/

Lever / Layer	Regenerate	Share	Optimise	Loop	Virtualise	Exchange
System/ general	• Poorly defined brief: What was the building: house/office/exhibition space? • More time needed: to test other circular strategies and for market investigation on circular products					
	• Natural ventilation • Non-toxic materials with low embodied carbon	• Design for deconstruction: avoid wet-trade construction • Take-back agreement with some suppliers allowed second life	• Maximise off-site fabrication	• Difficulty finding a second life for materials: selling place?	• Material passports recorded: - What it was - What was in it - Who made it - When they made it - What intent for second-life • Missed information: - volume of materials • BIM model: Revit® model but no time to put all information. "Having a digital repository acting as a single source of truth is essential" (RB) • No VR modelling: no time	• Take-back agreement with some suppliers: new business model
Site	• PV panels overshadowed by surrounding buildings					
Skin	• Renewable Accoya timber boards • Insulated cladding panels	• Accoya treated timber boards for durability • Design for deconstruction: Mechanical & push-fit Lindapter clamp connections to prevent damage (2017)	• Flat-packed CNC'd timber boards optimise storage, transport & construction			• New technology: CNC'd timber • Lindapter clamps never used before to support facades
Structure				• Reused steel beams		
Services	• Low-serviced building: only HVAC, electrics & lighting. No plumbing, toilet, appliances...					
	• LED low-energy lighting • PV panels (*ditto*) • Energy storage: battery allowed building to operate off-grid	• Plug & play connections: accessibility, flexibility & standardisation	• IoT: some lights controlled remotely & kept information on hours of use • Low voltage DC network with limited loads	• MVHR made of recycled materials	• IoT & virtual controls ran through Wi-Fi: "the most circular items are the ones that don't exist", RB	• New technology: plug & play connections • New technology: saline battery • No pay-per-lux light as a service: no time
Space			• Flexible space: based on the 7S 'shearing layers' concept and Japanese houses			
Stuff			• Flat-packed CNC'd plywood furniture	• C2C® Desso carpet with 70% recycled content		• New technology: CNC'd plywood

* The colour coding represents successes and regrets as expressed by interviewees.

4.2.2. Circular building services

The building was not heavily serviced, missing the opportunity to test what circularity means for toilets, plumbing, cooling, heating and appliances. This was regretted by RA and attributed to a poorly defined brief. Nevertheless, servicing was very successful in four areas: power, lighting, mechanical ventilation and, most remarkably, virtual controls. Power was delivered through a non-toxic, reusable saline battery connected to The Building Centre and roof PV panels, providing a low voltage DC network with 240V plug mains, limited circuit losses and no need for a transformer.

Low-energy appliances and lighting enabled this. A plug-and-play standardised USB connection system allowed interchangeability between devices and flexibility. All electric devices, including lights, were virtually controlled through Wi-Fi, some even remotely through apps, and they were interlinked and monitored through IoT technology.

Table 14 describes all circular services products included in the building as specified in the project's online material passport (Arup, 2016a). It is worth mentioning the handmade 3D printed-laser cut MVHR unit made of recycled parts. Even though it cannot be replicated at a commercial scale, it proves the potential of digital manufacturing. Sustainable Gatorduct cardboard ducts (Gatorduct, 2018) were used as part of the ventilation system and efficient, reusable and recyclable Xicato LED modules for lighting (Xicato, 2018a).

Table 12. TCB's building services products and their 'material passport'. Source: http://circularbuilding.arup.com/

System	Manufacturer / supplier	Circularity lever	Description / materials	Next life
MVHR unit	Arup	Loop/ exchange	Made with 3D printed-laser cut recyclable Perspex, recycled PET from bottles & reusable electrical motors for e-scooters	Re-use by Arup
Duct work	Gatorduct (2018)	Regenerate/ exchange	Highly sustainable cardboard duct comes from managed forests: for each tree chopped 2 new trees are planted	Re-use by Arup
Saline battery	Aquion Energy (2018)/ Circuitree (2018)	Regenerate/ exchange	C2C® certified, Aqueous Hybrid Ion (AHI™) technology made of non-toxic, abundant materials such as saltwater	Return to supplier
'XIM' LED lamp	Xicato (2018b)	Share/ Optimise/ Exchange	With run-time monitoring & storage capability. The entire module can be recycled. Lasts >50,000h with guaranteed colour & light output stability	Re-use by Arup
Circular Lamps	Arup, Xicato (2018a)	Share	Low-energy bluetooth-enabled lamps controlled from an app. Reclaimed component include kilner jars. Designed to be dismantled and their component parts re-used.	Re-use by Arup
Track spot lighting	Mike Stoane Lighting (2018)/ Arup	Share/ optimise	Simple design, efficient dissipation of heat, mechanical assembly fittings, & wireless light fitting control & sensing	Re-use
LED profile	8 Point 3 LED (2018)	Share	Remote phosphor light engine (the LED equivalent of a conventional lamp) allows replacement of installed fluorescent luminaires with efficient LEDs	Return to supplier
Digital control	Tinkerforge (2018), Raspberry Pi (2018), NXP (2018), Halcyon Microelectronics (2018)	Share/ virtualise/ exchange	Bluetooth low-energy wireless controls and 6LoWPAN communication (the technology behind IoT) to address each light fitting independently. The system is orchestrated by a Raspberry Pi processor: a consistent user interface for all the lights inside the building	Re-use by Arup

4.2.3. Project's findings

The project has been useful to raise new questions, discover barriers and absorb findings or propose solutions that can be applied to real commercial buildings. These are summarised in Figure 31. Most revolve around the barriers to circular procurement and the importance of information and digital technology.

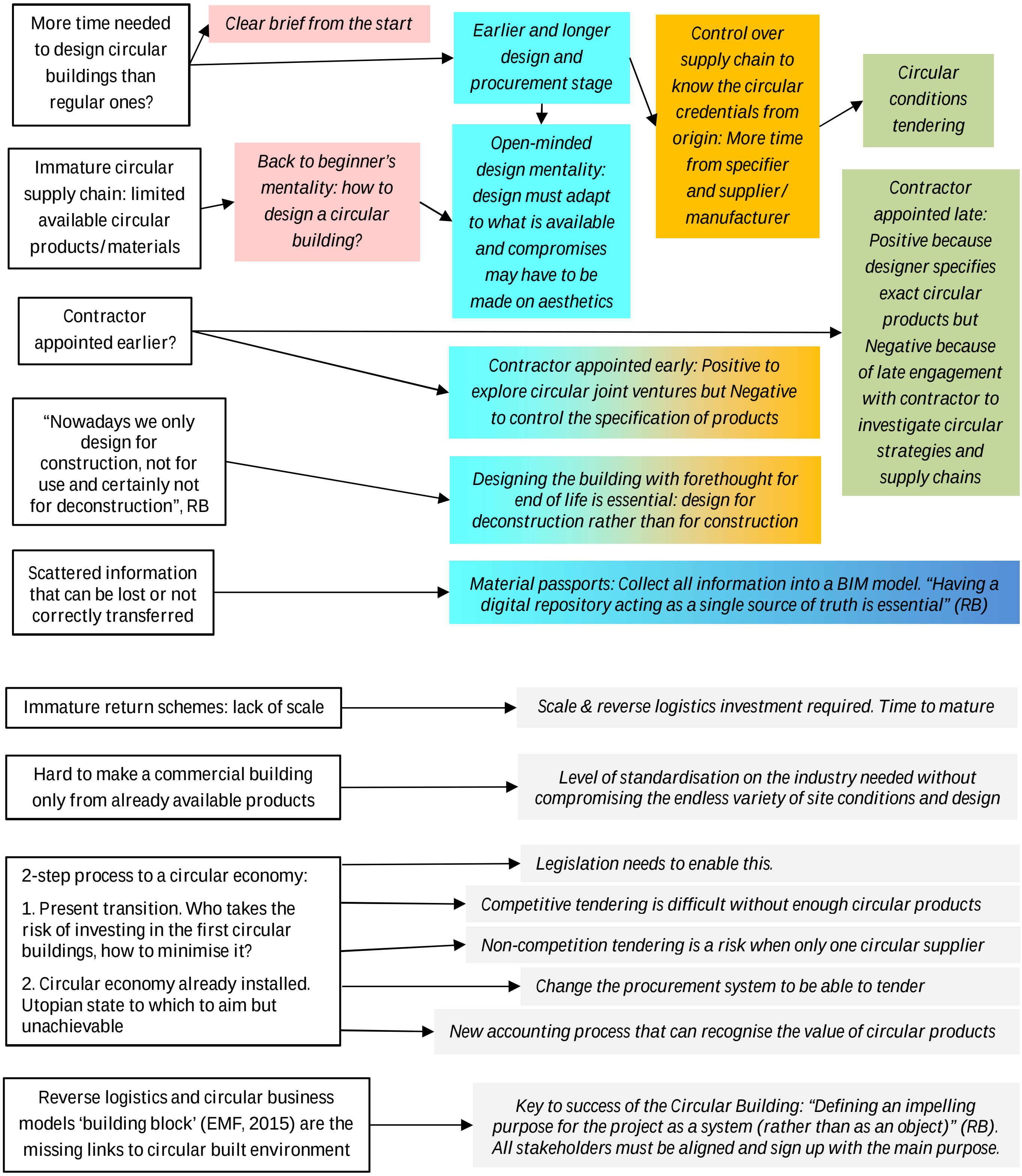

Figure 31. TCB's barriers/questions raised and their corresponding learnings/speculative solutions through RIBA stages. Blank boxes correspond to barriers/questions and filled boxes to learnings/solutions which are colour coded as per the RIBA stage whre they should be considered (Stages 0, 1, 2, 3, 4, 6 & 7). Grey boxes indicate solutions unrelated to the RIBA Stages.

5. Discussion and guidelines

5.1. Case studies comparison and circular achievements

Each of the analysed case study projects is different and this has been reflected in their findings and how they have been presented. 22 Gordon Street has served as an illustrative project to understand a business-as-usual commercial building process, although it did include refurbishment project-specific constraints that do not apply to typical new-builds. It followed a standard RIBA stage process, a currently common design and build procurement route (CIOB, 2010), had an extensive design team including a sustainability consultant (Expedition Engineering) and a medium-high budget. The refurbishment and extension brief with a focus on improving performance, the sustainability goals and the prominence of the client (UCL) make up an ideal scenario to use the project's process to frame generic circular guidelines for UCL and the industry to use in future projects. The findings from The Circular Building are intentionally complementary. Circular strategies, design features, construction methods, products used and findings from the experience can be used to populate the same generic guidelines.

Table 13 evaluates the circularity of the decisions taken at 22 Gordon Street (previously analysed in the Findings section) and compares them with The Circular Building's homologous strategies. Starting with the big changes suffered by the brief, a generally common circumstance in construction projects, the delay clearly proves an inefficient use of resources (human, time), but the final decision to invest more to achieve a longer-lasting value is highly circular. The use of BIM was not mainstream at the time of the project and that could have optimised the process and avoided coordination problems. The early decision to retain the concrete frame (analysed in the results section) was arguably the most resource-efficient and circular, as embodied carbon in structures can typically represent up to 50% of the whole building (Hitchin, 2013). Nevertheless, the reuse of steel beams at The Circular Building could have been replicated within the extension structures of 22 Gordon Street. These retention and reuse strategies could have been used for building services systems, but the immaturity of the secondary market and obsolescence of existing components would have made this difficult.

The circularity around building services varies between systems. Accepting the impossibility of fully passive cooling and ventilation, the mechanical solution was very focused on reducing the operational footprint by designing an energy-efficient centralised system and modulating flow via a BMS. Some circular decisions were taken, such as standardising the chilled beam units and virtualising controls, but a big circular opportunity was missed in the application of service contracts to the chillers and chilled beams.

The need for a new transformer to solve the extra power load could have been avoided by reducing the building's loads and installing a resilient renewable energy system with battery storage as demonstrated in The Circular Building. Again, the power network could have emulated the flexible plug-and-play connections, and the recyclable and interchangeable Xicato LED lighting modules. The decision to install 'gender-neutral' high quality toilets was very circular as it is a 'carbon investment' for the future. Fire safety decisions could have been more circular by avoiding the open staircase and the extra level, but spatial and architectural priorities had more weight.

In general, it is interesting how some decisions are ambiguous in terms of their circularity: they increased the need to install more components/services but reduced it in some other way. Also, project constraints, such as the ones involved in a refurbishment, can be important by imposing circular or non-circular conditions. E.g. the retention of the concrete frame. An extensive LCA would be needed to compare scenarios as a result of different design decisions taken, although speculations on future developments would always be required.

Table 13. Circularity evaluation of 22 Gordon Street's decisions against circular principles and The Circular Building's strategies

22 Gordon Street decision	Circular lever	Circularity	The Circular Building homologous strategy
Shifting brief/ Enhanced project: more investment	Optimise/ Share	Inefficient use of resources/ Increase utilisation. Safeguard against premature obsolescence	Similar problem: undefined brief
No BIM	Optimise/ Exchange	Technology that can improve resource, time & space efficiency and avoid coordination problems[1]	*Revit* BIM model used but lack of time to optimise
Retain concrete frame	Share/ Loop/ Optimise	The most circular decision. Saved embodied carbon and prevented waste, cost and energy, but also constrained services solutions (e.g. lifts)	Reuse steel beams from a previous life
Open-adaptable layout, reversible partition fixings & robust furniture	Share/ Loop	Open layouts & reversible partitions are flexible to future changes of use and space requirements. Robustness prolongs furniture value over time	Flat-packed CNC'd plywood furniture
Grey spaces and dense occupancy	Share	Increase occupancy rates efficiently is essential to avoid the need for new buildings/ more space	N/A
Open-social stairs	Optimise/ Optimise	Negative because it was not practically needed & led to more fire safety services. Positive because 'it avoided the need for a new lift'	N/A
No natural ventilation	Regenerate	Passive design is a priority to avoid building services in the first place	An MVHR unit was used instead as a showcase
District heating connection	Share	Can minimise the number of plant components but can increases circuit heat loss	N/A
User control over sealed strategy	Regenerate	Decreases energy consumption if correctly used but does not reduce the need for equipment	Virtual controls through Wi-Fi. IoT used to learn user behaviour & optimise even more the energy consumption & product's performance
Centralised UCL BMS control	Optimise/ Virtualise/ Exchange	Virtualises controls & can optimise consumption, consequently reducing the size of equipment & increasing product life	
Centralised AHU with heat recovery	Optimise	Centralised systems reduce the need for extra equipment & heat recovery, the need heating/cooling apparatus	3D-printed MVHR unit made of recycled materials. Distribution with *Gatorduct* low-embodied energy cardboard ducts
Standardised multipurpose chilled beam units	Optimise/ Share/ Loop	Multipurpose unit is more space efficient, simplifies responsibility in one manufacturer & the standardization allows for easier replacement	
No service contract for chillers & chilled beams	Exchange	Responsibility retained on the supplier, improving maintenance, performance & end-of-life recovery	None, given project's temporary nature
Extra fan coil units	Optimise	Lack of coordination/ risk management problem	N/A
New substation & transformer	Share/ Exchange	+ embodied carbon & energy loss. Should lower power load & use new technologies. E.g. batteries	Low voltage DC network and saline battery
New fibre connection & comms rooms	Virtualise/ Exchange	New wireless technologies should replace fibre wiring & cloud storage, local comms rooms	All ran through Wi-Fi. Unknown if cloud storage
New efficient LED lighting	Optimise/ Exchange	New & evolving technology reduces energy consumption & unwanted heat	Recyclable, plug-&-play LED modules virtually controlled & monitored
Standardised gender-neutral toilets	Share	Easier to replace if all standard size. Gender-neutral design against premature obsolescence	N/A
High quality toilets	Share	Prolong life through low maintenance & durability	
New centralised DHW with no water storage	Share/ Optimise	Better to reuse existing or share with other buildings. Centralised optimises materials & space	
Escape distance <18m	Optimise	Design out the need for sprinklers	N/A
Last floor height >18m	Optimise/ Optimise	Need for fire-dedicated core is resource inefficient but optimizes space by maximizing planning height	
Only 2 lifts: waiting times accepted	Optimise/ Share	Less embodied carbon in the short term but can increase it in the long term for lack of flexibility	N/A

*The colour coding represents positive and negative impacts on the circularity of the building and its services

[1]BIM is a technology that provides some capabilities, but it cannot be directly established to perceived benefits (improved efficiencies, clash detection, etc) and improve the coordination. There are still significant gaps on the use of BIM in that regard.

5.2. Guidelines

Using the findings from the literature review and the case studies, this study finally aims to answer general questions on the design and procurement of circular building services: How should circular building services be designed and specified? What should the procurement criteria hierarchy be? And finally, how do these decisions fit in the design and procurement process?

First, the most circular services are the ones that do not exist. So, designing them out through passive measures is the most effective strategy. This is generally true but, if the passive measure involves increasing materials in other parts of the building, it could offset the carbon footprint. E.g. Embodied carbon in concrete structures is estimated to be approximately in a 10/1 ratio against HVAC systems. If thermal mass is increased by more than 10% to avoid mechanical air-conditioning, the carbon savings would be reduced (Hitchin, 2013). (This is later suggested as a subject for future work.)

If building services are installed, the first procurement criteria would be for durability/life prolongation. This means specifying high-quality, robust products that require low maintenance but that are also designed against premature obsolescence. Strategies for this include modularity, standardisation and demountability of products and their component layers to allow for upgrading, altering aesthetics and replacing faulty parts. Resource efficiency comes next by leveraging digital technologies such as 3D printing and robotics on the production side, BIM to help coordinate and preserve accumulative information on design for later use by the FM and the reverse supply chain, and BMS to control and minimise energy usage during operation. 'Low-tech' approaches such as specifying products that use sustainably sourced materials (renewable and low-embodied) are also equally valid.

Finally, the last four criteria consist of the three outer loops of the circular butterfly diagram (EMF, 2015): reuse, refurbish/retrofit and recycle. To facilitate a valuable end-of-life recovery, systems and components should be designed for deconstruction with mechanical and standard fixings that do not damage other components (as seen in The Circular Building), and use modular shapes, sizes and non-toxic materials.

One of the biggest drivers to allow these procurement criteria to embed into the supply chain is changing business models from product to service. Retaining ecological responsibility with manufacturers instead of passing it to consumers aligns economic with environmental benefits and resource efficiency.

The diagram in Figure 32 summarises these procurement criteria.

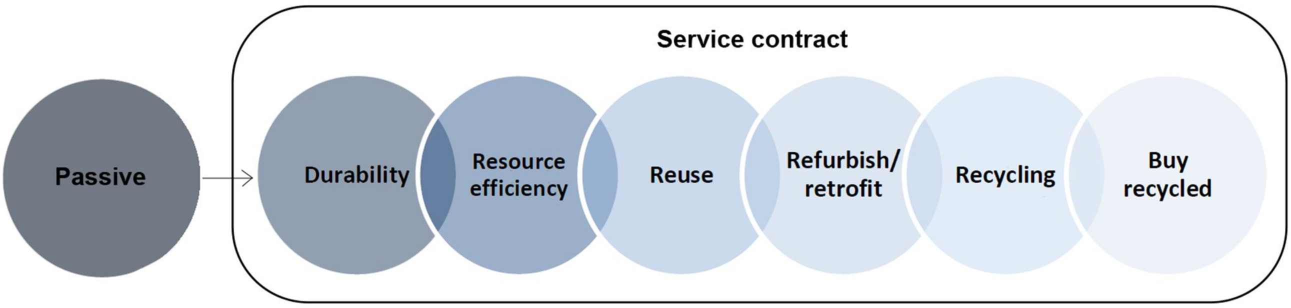

Figure 32. Circular procurement criteria hierarchy adapted to building services
Adapted from: Circular Procurement- Best Practice Report (Jones, Kinch Sohn and Lysemose, 2017)

Given the immaturity of the circular market, making these decisions early on contributes to the level of circularity achieved and minimises risks. Circular procurement can often be time consuming, in order to ensure the buildability of the design, check circularity credentials of products and manage service/take back contracts with suppliers. As seen with The Circular Building, designs may need to adapt to what is available.

Also, early design decisions create a trajectory that can lock in the benefits from the beginning, whereas leaving these considerations for later stages involves expensive and inefficient redesigning, adaptation or eventually: waste. For instance, a building component designed for easy disassembly requires much less effort to convert into reusable and recyclable components than one designed as an indivisible composite requiring energy-intensive end-of-life processing. The graph in Figure 33 reflects the cumulative environmental impact of decisions at different stages of design.

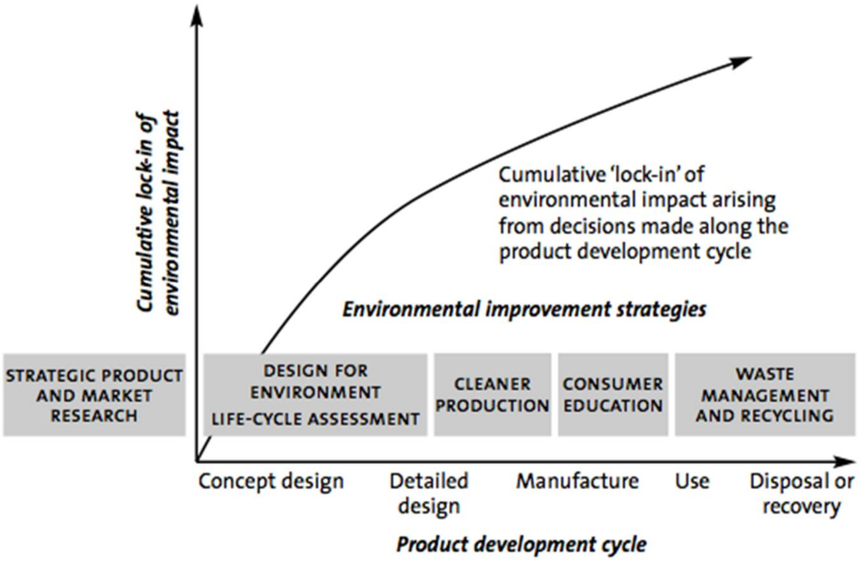

Figure 33. Cumulative environmental impact of decisions at different stages of product design.
Source: Design + Environment: A Global Guide to Designing Greener Goods (Lewis *et al.*, 2001)

Using 22 Gordon Street's decision-making process as a framework and the strategies and findings from the literature review and The Circular Building as the content, Figures 34-41 attempt to produce a set of prototype guidelines describing what decisions must be made at each step of the RIBA process and what stakeholders should take part in the discussion to improve the circularity of the building and particularly its services. Note how decisions that are generally taken later on in a business-as-usual process, are moved forward to lock circularity into the project and allow for contingencies.

It is key to communicate the intention of achieving a circular building from the start with clear strategies and objectives defined in the brief. Also, imposing on the design team that they use BIM and store valuable product and design information throughout the process, establishing a circular procurement criterion and they explore the market at an early stage to suggest service/performance contracts with suppliers. As gathered from The Circular Building findings, it is important to maintain an open-minded design mentality and adapt to currently available circular products.

All these measures, indicated in Figure 34, could have changed the design of 22 Gordon Street by selecting other products and materials. E.g. reuse steel beams for the extension structure or Accoya timber panels for internal fittings or even external cladding (subject to planning consent). Also, these would be stored in digital material passports to help the FM team with maintenance and a valuable future end of life recovery.

Regarding the space planning and fitout, most of the decisions taken for 22 Gordon Street have been translated into Figure 35's guidelines. They do represent a positive way of designing for robustness, quality and flexibility to future changes. As an addition, on-demand space-sharing schemes for the offices or studios could have been explored to further raise the occupancy rate of the building and service or take-back contracts suggested to fitout suppliers (as in the New Venlo City Hall case study).

Brief & procurement

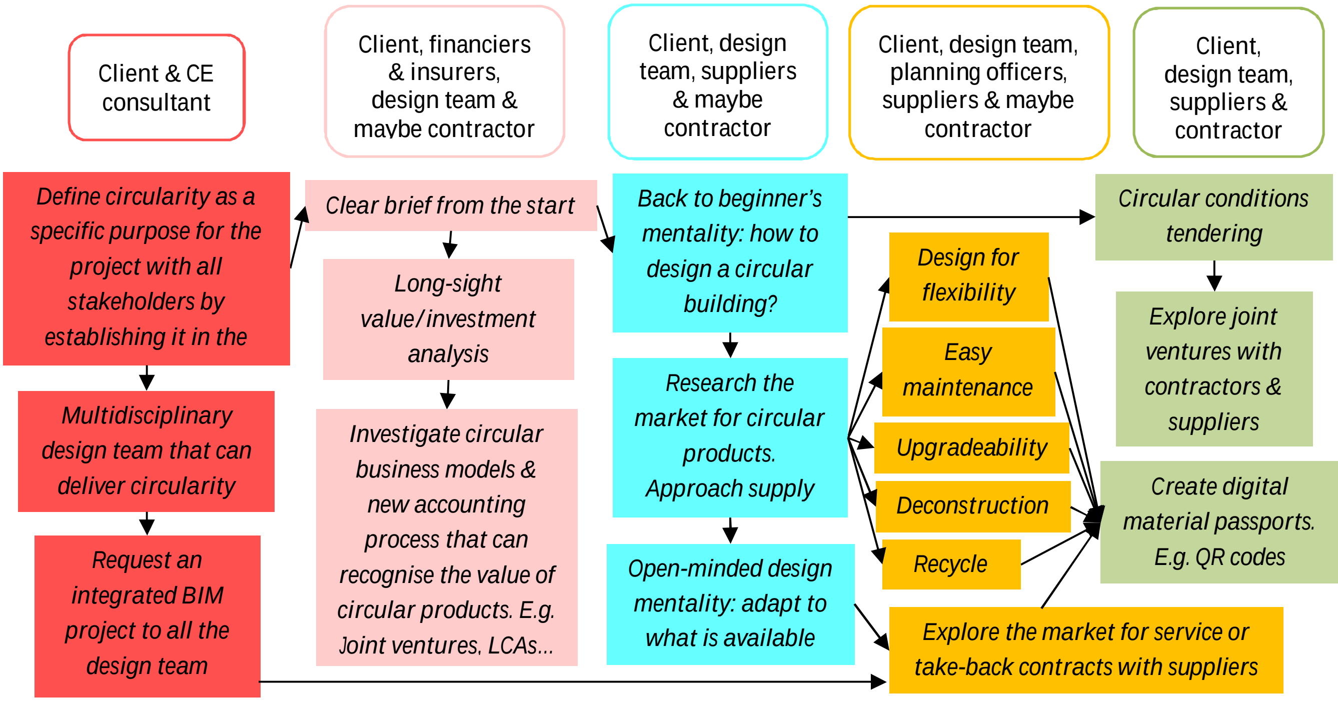

Figure 34. Guidelines for a circular approach to brief & procurement process through RIBA stages
*Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages 0, 1, 2, 3 & 4

Architecture/space layout design strategy

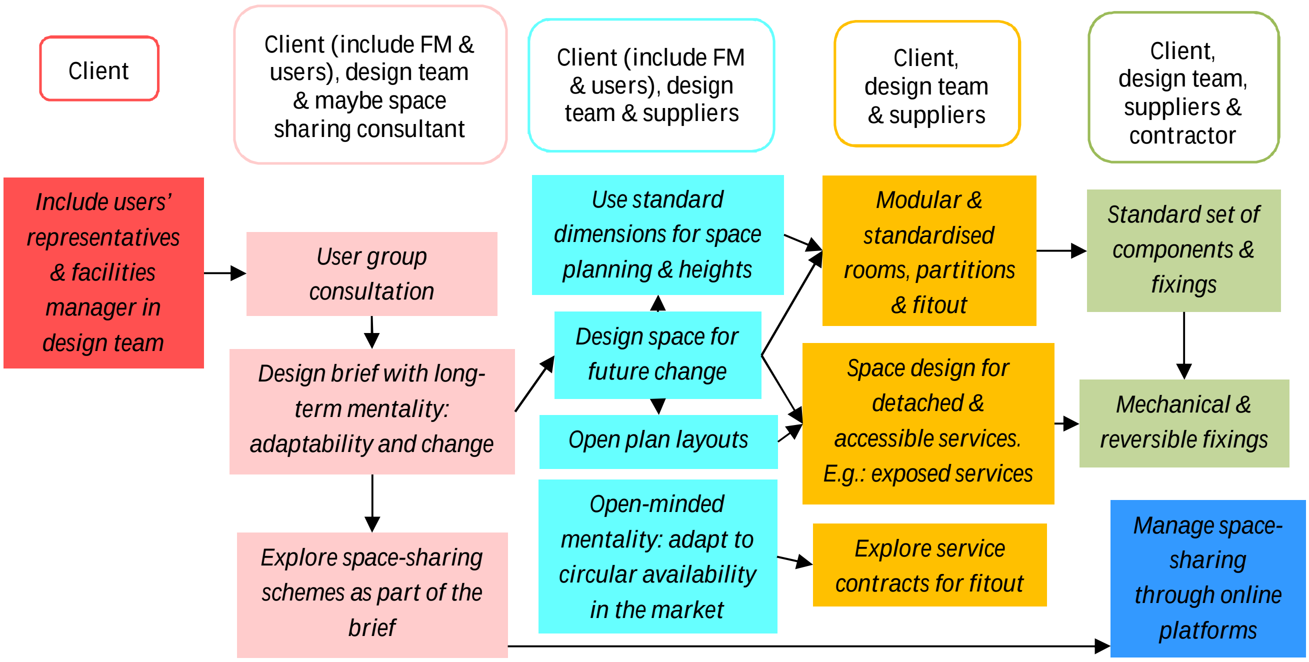

Figure 35. Guidelines for a circular approach to space planning and design through RIBA stages
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages 0, 1, 2, 3, 4, 6 & 7

For the HVAC strategy guidelines described in Figure 36, it is important to note that, although in this specific building relying only on passive ventilation would not work (mainly because of the high occupancies), it should be explored for any other project. The same applies to designing mechanical heating or cooling out, subject to occupancy and site climatic conditions. If mechanical HVAC systems are required, exploring district heating/cooling systems can be beneficial but, as discovered in 22 Gordon Street, taking that route can frustrate service/performance contracts with AHU, chiller or local unit suppliers. For instance, if a contract would have been achieved with FlaktWoods for the chilled beams, some of the current commissioning problems could have been avoided.

The power and lighting strategies in Figures 37 and 38 suggest to first reduce to the minimum the energy and artificial lighting requirement of the building and then test self-sufficiency options through renewables and batteries like in The Circular Building. Again, service contracts could be explored with the PV, battery, transformer or lighting suppliers (e.g. Philips pay-per-lux), or demountable/recyclable appliances selected (e.g. Xicato luminaires). Digital controls and BMS can then be used to help reduce energy consumption.

HVAC strategy

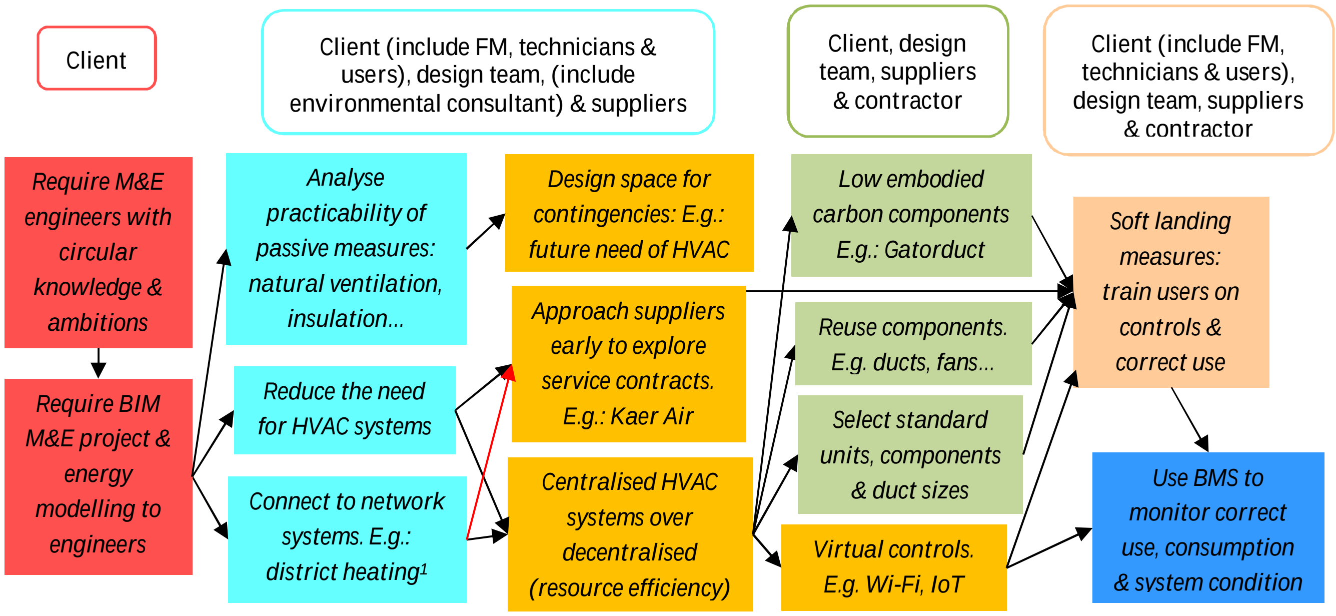

Figure 36. Guidelines for a circular approach to the selection of the HVAC strategy and specification through RIBA stages
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages 0, 2, 3, 4, 6 & 7
[1]Decision to connect to network systems may obstruct a service contract with an HVAC supplier due to responsibility conflicts

Power strategy

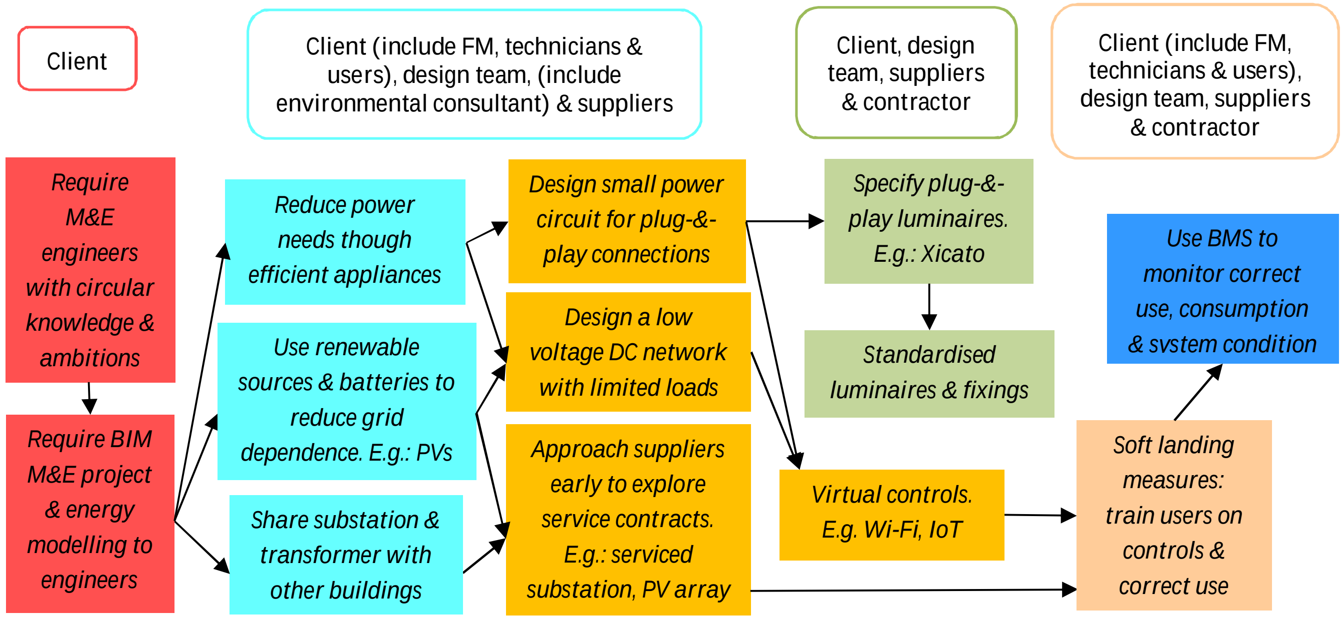

Figure 37. Guidelines for a circular approach to the selection of the power strategy and specification through RIBA stages
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages 1, 2, 3, 4, 6 & 7

Lighting strategy

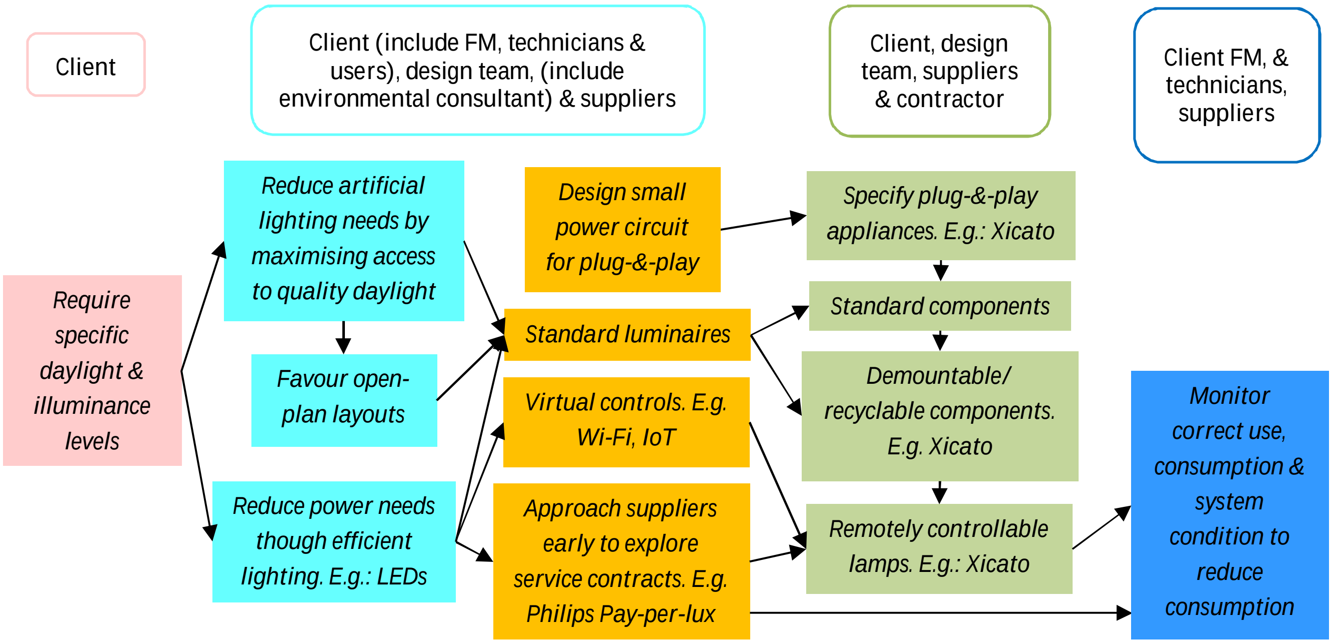

Figure 38. Guidelines for a circular approach of the lighting strategy and specification through RIBA stages
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages 1, 2, 3, 4 & 7

Toilet decisions taken for 22 Gordon Street have been incorporated into Figure 39 as they intend to safeguard against high maintenance and (socio-political) obsolescence. Some plumbing products such as pumps and circulators could have been sourced from Grundfos with service or take back contracts and the pipework specified with sustainable materials, reused or designed for future reuse.

Plumbing strategy

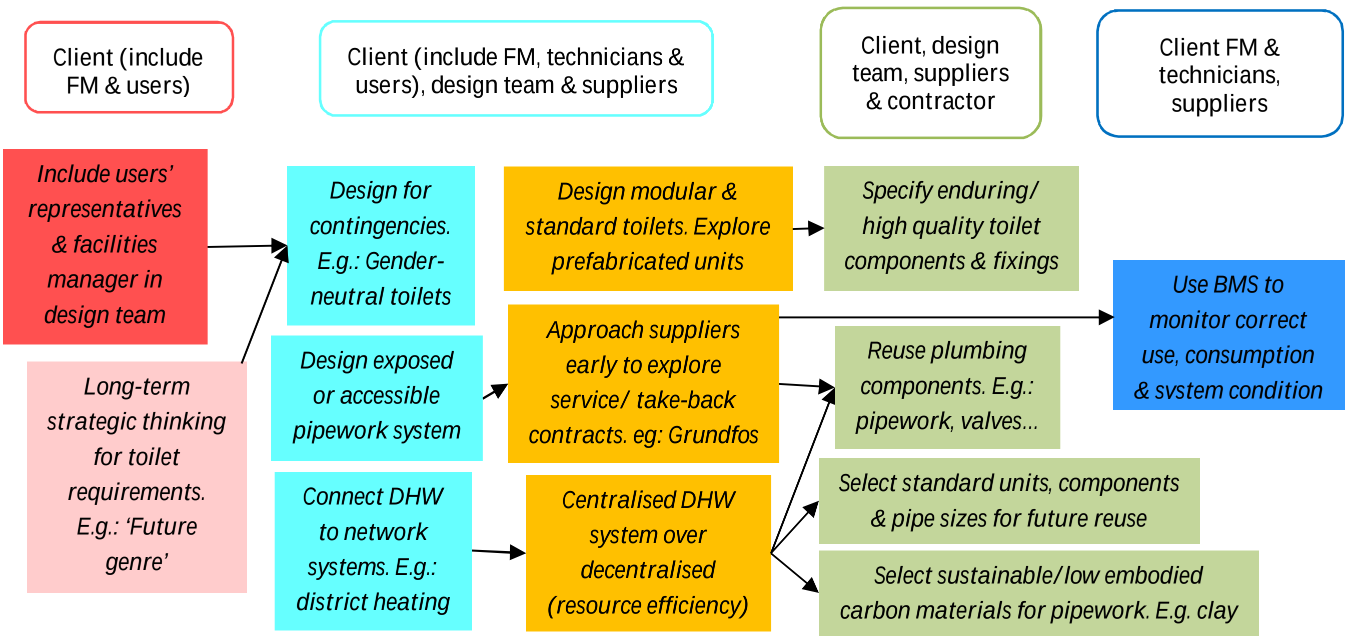

Figure 39. Guidelines for a circular approach to the selection of plumbing solutions through RIBA stages, including toilets, pipework and the DHW strategy
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages 0, 1, 2, 3, 4 & 7

The fire-engineering strategy guidelines are difficult to consider as designing out fire control, extinguishing or evacuation systems reduce embodied carbon but can imply cutting the building's height (not maximising the site's usable space) or making sacrifices to the design (e.g. open atrium stairs). The only factual guideline in this regard is to understand fire building regulations from the start and/or involve a fire engineer to incorporate fire requirements into the design from the start and avoid late surprises (see Figure 40).

Fire-engineering strategy

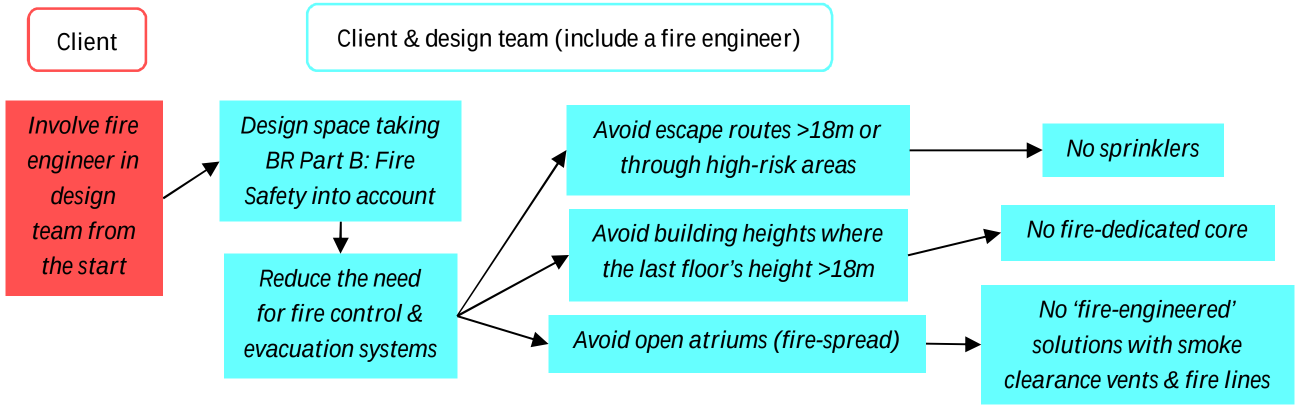

Figure 40. Guidelines for a circular approach to the selection of the fire-engineering strategy through RIBA stages
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages **0** & **2**
Source: Building Regulations Part B: Fire Safety (HM Government, 2009)

It is difficult to extract generalised guidelines from the vertical transportation strategy for 22 Gordon Street given the specific constraints. Lift provision and waiting times should be calculated early on and a degree of flexibility for future increases in occupancy considered. Service contracts should also be explored with lift suppliers as they require high maintenance and the technology becomes obsolete very quickly. Lift shafts and elevators should be designed for easy replacement and upgrade with new models (see Figure 41). 02084587444

Vertical transportation strategy

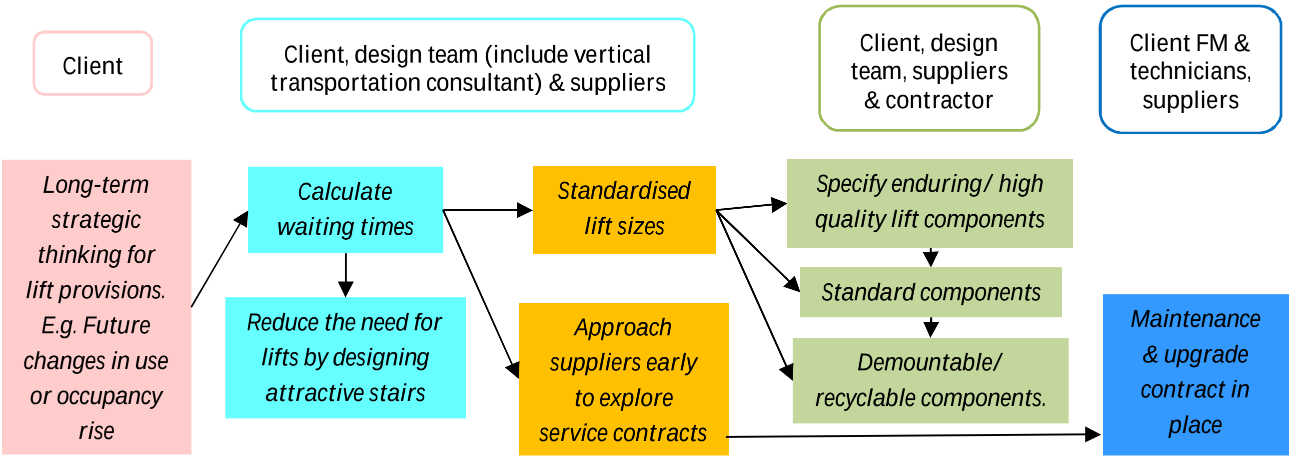

Figure 41. Guidelines for a circular approach to the selection of the vertical transportation strategy through RIBA stages
* Upper bubbles indicate stakeholders. Decisions are colour coded as per the RIBA Stages **1**, **2**, **3**, **4** & **7**

To finalise, a leap into the future is taken to propose how the RIBA Plan of Work could look like in a functioning circular economy. The diagram in Figure 42 reflects the looping nature of circular procurement and whole-life-cycle concept. In this scenario, the current 2013 Plan would cover up to the middle of the process and new reverse logistics stages would fill in the other half, completing the loop and eliminating the responsibility gap between the 'In Use' stage and the 'Strategic Definition' origin. Replicating the logic behind the 'butterfly diagram' (EMF, 2015): the wider the loop, the less building value retained and the further back the process must restart from.

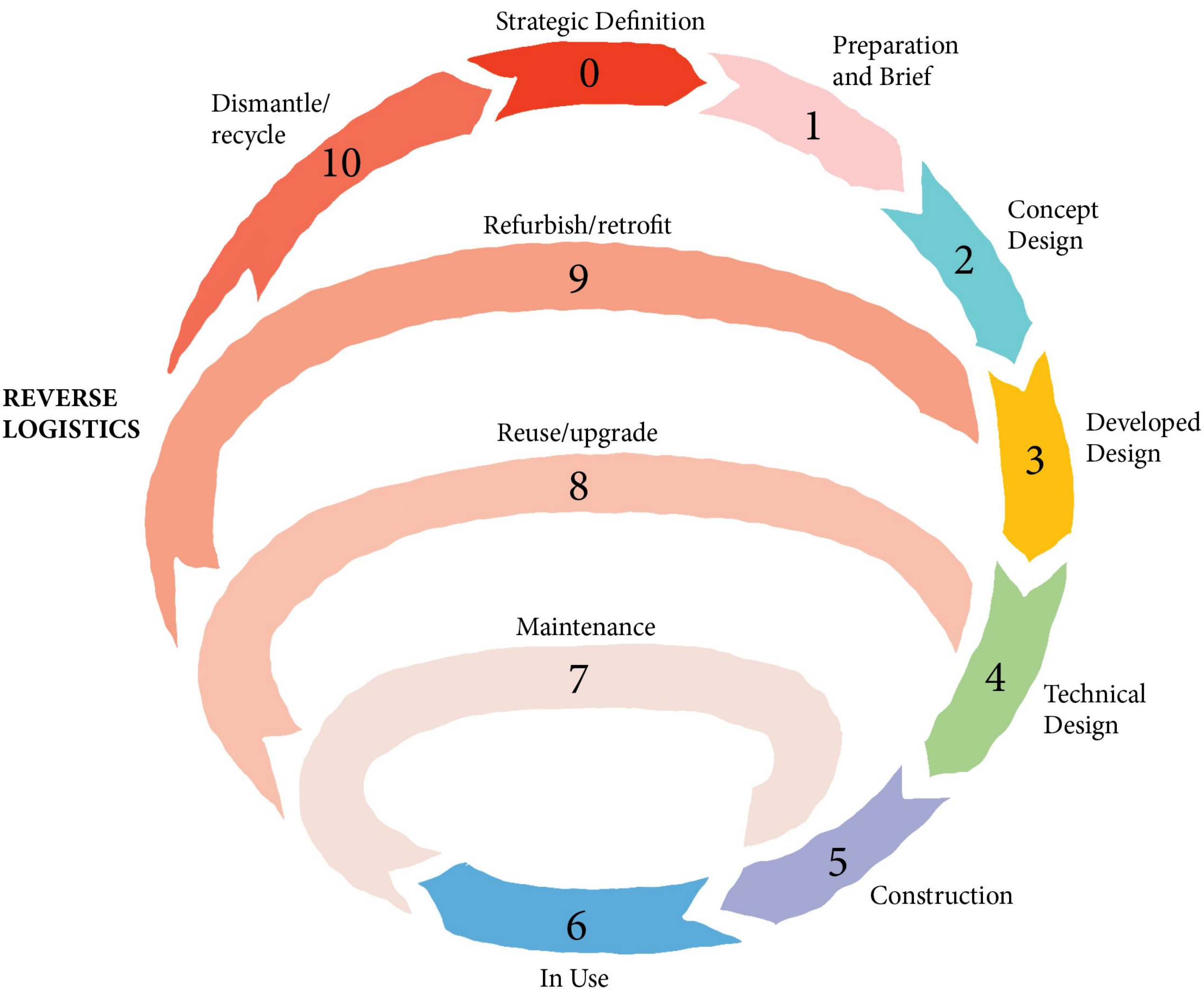

Figure 42. Prototype adaptation of the 2013 RIBA Plan of Work to a circular closed-loop design and procurement process

6. Conclusions and future recommendations

It is difficult to uncover the exact way to design and specify building services systems to maintain them at their highest utility value given the uncertainties on future trends, but the strategies depicted in this study are certainly a way forward. Durability and resilience are the key characteristics of good circular design. For example; robust ducts, pipes and cables, and easy to maintain equipment made of modular components so that they can be upgraded if technology evolves. But designs need to be prepared to fail or become obsolete, meaning that products must be able to be safely and effectively dismantled so to recover their components or materials at their highest value and be used in a second life. E.g. The demountable Xicato LED modules or the Lindapter clamps fixing method.

To accelerate this change, many drivers and system changes have been discussed throughout this paper, but these can be narrowed to two main priorities: information through digital technology, and the product as a service business model shift.

BIM is still evolving, but it has a big potential to transform the design and management of the built environment and the resource assets embedded in it. Once all its functions have been unlocked in the so called BIM Level 3 or 7D (BIM Industry Working Group, 2011) and all stakeholders are integrated in the same methodology, it will allow a life-cycle management of buildings where a digital 'twin' will help uncover the real building's risks through data gathering and simulation. The design team can populate it during design and transfer it to the contractor and suppliers to adapt it during construction. It will store design, procurement, construction, commissioning and soft-landing information, all carried on to the facility management team who can continue to update the database with maintenance information. All can finally be used by a 'reverse logistics contractor' to recover the value of the assets at the end-of-life, and transfer each component's accumulated information to its new repository. It is essential for this to be "a single source of truth" (RB) as opposed to having information scattered in different mediums (e.g. Revit, Excel, CAD…).

On the other hand, service contracts retain ownership and 'ecological responsibility' on the supplier's side instead of transferring it to the 'end user'/consumer, therefore aligning economic with ecological interests. As seen with the traditional procurement of chillers and chilled beams at 22 Gordon Street though, there are always barriers to implementation: Risk adversity, contractual liabilities and the interdependence of different parts of the system to achieve good performance, can discourage both building owners and suppliers. To avoid this, conversations with suppliers must start early on before design decisions have been locked into the project and contracts must be carefully thought through with the collaboration of cost surveyors, insurers and financiers.

Time and poorly defined brief, were key problems flagged by The Circular Building's interviewees. Does designing circular buildings require more design and procurement time? Given the immaturity of the market and the uncertainties behind the procurement process, an early exploration into the market with precise circular criteria is required, decisions on the brief and circular targets must be taken early in the process and the design must be able to adapt to what is available.

Some strategies and decisions have been uncovered in this study, but the nature of the new business model and associated contracts between stakeholders, the risk management and the distribution of responsibilities are still unclear. It requires will, expertise, long negotiations and risk taking. For this reason, not only developers, designers, contractors and suppliers are required, but also finance and insurance companies, to manage the risks. Academics need to propose a course of action and government and professional bodies need to produce policies and guidelines for the industry. Construction process frameworks, such as the RIBA Plan of Work, must evolve to reflect the circular nature of buildings, implying through their guidance that the responsibility of design and procurement does not end after construction. Buildings must also be designed for deconstruction.

6.1. Future work and recommendations

A logical next step to this study would be to generate an interactive 3D guidelines tool where someone can track each step of the design process and see together the decisions that must be taken, who should be involved and why (the circular benefit).

Hereafter, future work could focus on how to improve the circularity of specific building services systems/products that were used in 22 Gordon Street or that are specified for any future UCL building such as the Marshgate Building. For instance, further conversations with FlaktWood (the chilled beam manufacturers) could help understand how to work out a future service contract with them. Other partnerships could follow up with other suppliers to develop circular services including: luminaires, transformers, PV panels, batteries, ducts, pipework and lifts. The final goal would be to create a network of manufacturers and suppliers that can provide UCL with circular solutions and products.

Simultaneously, further engagement with UCL Estates, Arup and the Marshgate design team to translate the findings from all these studies and partnerships can help improve the circularity of building services in that project and in any future UCL development. There is an opportunity to unlock the power of UCL as an influential real estate developer to lead the change in the market towards sustainability and circular economy. Again, a network of professionals with circular economy expertise and experience would allow an exchange of information and spread the knowledge through the sector. An attempt to kick-start this network of circular economy experts and an inventory of circular products and manufacturers that UCL can contact has been included in the Appendix.

In the wider context, this study has left some unanswered questions regarding circular building services that are recommended to further investigate the subject:

- A balancing exercise of optimisation between passive and active design measures that takes into account the LCA but also criteria such as user comfort, controls or future resilience.
- What should the technical specifications for tendering circular building services look like?
- How can we measure circularity and develop proper assessment tools that take into consideration building types and project-specific constraints (e.g. refurbishment)? Recently, a joint report between consulting companies Circle Economy, Metabolic and SGS Search, and the Dutch Green Building Council (DGBC) suggested circular indicators for inclusion in BREEAM NL, where specific desired outcomes/impacts and strategies are clearly defined (Kubbinga *et al.*, 2018).
- What circular business models are better suited for each building services system?
- What contractual relationship between the different stakeholders is better suited to align all interests and achieve circularity? How can supply and maintenance contracts work?
- How are the risks mitigated/managed?

6.2. Impact

During the project Si-Joe Portal and Ben Croxford, along with Ben Stubbs from UCL Estates were able to attend, present initial findings from this process, and contribute to a Bauhow5 Circular Economy event at the Technical University of Delft (TUDelft).

A Circular Economy in the Built Environment themed meeting at UCL HereEast in November was held where academics and estates staff from both TUDelft and UCL considered issues arising from this report.

7. BIBLIOGRAPHY

8 Point 3 LED (2018) *8 Point 3 LED*. Available at: https://www.8point3ledltd.com/ (Accessed: 10 October 2018).

Accoya (2018) *Innovation in wood*. Available at: https://www.accoya.com/ (Accessed: 29 August 2018).

Aquion Energy (2018) *Aquion Energy*. Available at: http://aquionenergy.com/technology/deep-cycle-battery/ (Accessed: 10 October 2018).

Arup (2016a) *The Circular Building*. Available at: http://circularbuilding.arup.com/ (Accessed: 20 August 2018).

Arup (2016b) 'The Circular Economy in the Built Environment', pp. 1–93.

Autodesk (2018) *What is BIM?* Available at: https://www.autodesk.com/solutions/bim (Accessed: 20 August 2018).

Baker-Brown, D. (2017) *The Re-use Atlas*. RIBA Publishing.

BIM Industry Working Group (2011) *BIM - Management for value, cost & carbon improvement*. doi: 10.1524/teme.2010.0045.

Brand, S. (1994) *How Buildings Learn: What Happens After They're Built*. Viking Press.

Braungart, M. and McDonough, W. (2018) *C2C Certified*. Available at: https://www.c2ccertified.org/ (Accessed: 20 August 2018).

BRE (2018) *Green Guide to Specification*. Available at: https://www.bre.co.uk/greenguide/page.jsp?id=2069 (Accessed: 20 August 2018).

Cheshire, D. (2014) *TM56: Resource efficiency of building services*.

CIBSE (2009) *Guide H Building Control Systems*. London: CIBSE Publications Department. Available at: http://www.loc.gov/catdir/bios/wiley047/93021609.html.

CIOB (2010) *A Report Exploring Procurement in the Construction Industry*.

Circuitree (2018) *Aquion Energy*. Available at: http://www.circuitree.co.uk/our-chemistries/ (Accessed: 10 October 2018).

DCLG (2007) *Building a greener future: policy statement*, *Nature Climate Change*. doi: 10.1038/nclimate3178.

EMF (2015) *Growth within: a circular economy vision for a competitive europe*. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf.

EMF (2016) *Circularity in the Built Environment: Case Studies*. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/Built-Env-Co.Project.pdf.

EMF (2017a) *A New Textiles Economy: Redesigning Fashion's Future*. doi: 10.1007/978-3-319-52311-8_1.

EMF (2017b) *Ellen MacArthur Foundation case studies*. Available at: https://www.ellenmacarthurfoundation.org/case-studies (Accessed: 22 June 2018).

EMF (2017c) *The new plastics economy: rethinking the future of plastics & catalysing action*. doi: 10.1103/Physrevb.74.035409.

FlaktGroup (2018a) *IPSUM optimization system*. Available at: https://www.flaktgroup.com/en/products/air-management--atds/ipsum-optimization-system/stip/ (Accessed: 10 October 2018).

FlaktGroup (2018b) *Stella exposed chilled beam*. Available at:

https://www.flaktgroup.com/en/products/air-diffusion-/chilled-beams/exposed-active/stella/ (Accessed: 10 October 2018).

Gatorduct (2018) *Gatorduct*. Available at: https://www.gatorduct.com/ (Accessed: 29 August 2018).

Grundfos (2017) *Sustainability report*.

Guldmann, E. and Remmen, A. (2018) *Towards Circular Business Models: Experiences in Eight Danish Companies*. Available at: http://vbn.aau.dk/en/persons/pp_f51ec2af-7fd0-4f1a-9a9a-b6ca165eba12/publications.html.

Halcyon Microelectronics (2018) *Halcyon Microelectronics*. Available at: https://www.halcyonmicro.com/ (Accessed: 10 October 2018).

Hawkins Brown (2013a) *UCL Wates House Refurbishment and Extension - Design Brief*.

Hawkins Brown (2013b) *UCL Wates House Refurbishment and Extension Stage C Report*.

Hawkins Brown (2014a) *UCL Wates House Major refurbishment and extension Design and Access Statement*.

Hawkins Brown (2014b) *UCL Wates House mayor refurbishment and extension - Stage D Report*.

Hitchin, R. (2013) *Embodied Carbon and Building Services*.

HM Government (2009) *Approved Document B - Fire Safety Volume 2 – Buildings ther than Dwellinghouses*, *The Building Regulations 2010*. doi: 10.1016/B978-0-7506-8580-1.00027-0.

Homij (2018) *Circular new-build Alliander BREEAM-NL Outstanding*. Available at: https://www.homij.nl/nl/nieuws/detail/circulaire-ver-nieuwbouw-alliander-breeam-nl-outstanding (Accessed: 2 July 2018).

Jones, M., Kinch Sohn, I. and Lysemose, A.-M. (2017) ‘Circular Procurement’, *Ministry of Infrastructure and the Environment*, (March), pp. 1–26.

Kaer (2017) *Kaer Technology*. Available at: https://www.kaer.com/technology (Accessed: 22 June 2018).

Kubbinga, B. *et al.* (2018) *A framework for circular buildings*.

Lewis, H. *et al.* (2001) *Design + Environment: A Global Guide to Designing Greener Goods*. 1st edn. Greenleaf Publications.

Lifschutz Davidson Sandilands (2011) *UCL Bloomsbury 2020 Masterplan*.

Lindapter (2017) *Lindapter Girder Clamp*. Available at: http://www.lindapter.com/Products/Girder_Clamp/1/Type_GC_Girder_Clamp (Accessed: 29 August 2018).

Livescribe (2017) *Livescribe 3 Smartpen*. Available at: https://www.livescribe.com/uk/ (Accessed: 20 August 2018).

Mackerness, D. (1999) *Evaluating the three models for the provision of air-conditioning in Asia*.

Madaster (2018) *Madaster*. Available at: https://www.madaster.com/en (Accessed: 2 July 2018).

Marmot, A. (2010) *University College London Space Utilisation Study*.

McIntosh, A. and Roberts, G. (2012) *Whole-life Carbon Footprint Measurement and Offices*.

Mike Stoane Lighting (2018) *Mike Stoane Lighting*. Available at: https://www.mikestoanelighting.com/ (Accessed: 10 October 2018).

Mul, P., Roos, S. and Jutte, J. B. (2016) *Opportunities and barriers for circular procurement in the built environment*.

NXP (2018) *NXP*. Available at: https://www.nxp.com/ (Accessed: 10 October 2018).

Philips (2017) *Schiphol Airport opts for Circular lighting : a responsible choice*.

Raspberry Pi (2018) *Raspberry Pi*. Available at: https://www.raspberrypi.org/products/ (Accessed: 10 October 2018).

RIBA (2013) 'RIBA Plan of Work'. Available at: www.ribaplanofwork.com.

Schneider (2018) *EcoStruxure™ Building Operation*. Available at: https://www.schneider-electric.com/en/work/solutions/enterprise-solutions/solutions/enterprise-software-suites-building-operation/ (Accessed: 10 October 2018).

Signify (2018) *About*. Available at: https://www.signify.com/global/about (Accessed: 20 June 2018).

The Building Centre (2014) *WikiHouse 4.0*. Available at: https://www.buildingcentre.co.uk/exhibitions/wikihouse-4-0 (Accessed: 22 June 2018).

Tinkerforge (2018) *Tinkerforge*. Available at: https://www.tinkerforge.com/ (Accessed: 10 October 2018).

WRAP (2014) *Resource efficient construction (Banbury: Waste and Resources Action Programme)*. Available at: http://www.wrap.org.uk/content/resourceefficient-%0Aconstruction (Accessed: 12 June 2018).

Xicato (2018a) *Xicato*. Available at: http://www.xicato.com/ (Accessed: 29 August 2018).

Xicato (2018b) *XIM LED module*. Available at: http://www.xicato.com/light-sources/xim-led-module (Accessed: 10 October 2018).

8. APPENDIX

The following supporting information is included in this section:

- The complete set of interview questions.
- A review of contacts that can help with information transfer and influence the circularity of future UCL and Arup buildings.
- A review of all products and manufacturers (circular and regular) used in both case study buildings.

8.1. Question development for 22 Gordon Street

8.1.1. General brief and decision-making

- Were there things in the original brief that changed by the final design such as going from natural ventilation to sealed windows? Who was driving those decisions? When was the decision made?
- Were there sustainability requirements in the brief? Did anyone from the school of architecture push for sustainability?

- Are there any parts of the building where decisions were particularly sustainable?
- Were there any discussions about climate change and future external temperature changes?
- What was your contribution to the design conversation?
- In your mind, who were the main decision makers, when were they involved in the project and what decisions were they?

8.1.2. HVAC-specific

- Did the decision of retaining the concrete frame stop you from doing certain ventilation strategies in the existing building?
- Everything had to be improved to Building Regulations standards. Did that apply to HVAC systems?
- Where there any circular solutions considered? What were the conditioning specifications in the brief?
- At Stage C, MVHR spandrel-integrated units were envisioned for the office spaces. When and why did that idea change?
- Was cooling capacity a bigger decision driver than energy consumption for deciding on the chilled beams solution?
- Was there any preference (aesthetics) from the part of the architects or the dean?
- Would “chilled/active beams as a service” solve the issues?
- If you were to go back would you change anything in particular to improve the chilled/active beams?
- What was the ventilation option taken for the potential hot spot at the top of the main stairs?

8.1.3. Other building services

- What decisions on other services such as plumbing, toilets, electrics, lifts, fire were taken early on?
- Was there any specific lighting specified or did you decide to accept the standard lights that came with Flakt’s chilled beams?
- Does the workshop in the ground floor have different power requirements? There was a new transformer installed. Was this a decision based on the new power requirement?
- Was the transformer part of the UCL’s budget for the building?
- What were the requirements on electric distribution and power points?
- What kind of flexibility was given to the electrical installation? Is the building assumed to be fixed? Was there any thought given to the fact that as architecture discipline or educational sector change in the future, the building could adapt to these changes?
- Are there any servers in the building?
- Is there hot water usage? Is DHW centralised here?
- Was the plumbing completely redone?

- Any decisions on using special material for plumbing? Any circular decisions on using long lasting copper instead of PVC? Was the Green Guide Standards[5] used to choose low embodied energy materials for example?
- What was the requirement for PVs?

8.2. Question development for The Circular Building

8.2.1. General brief and decision-making

- What was your role on the design and decision-making of The Circular Building?
- What did circularity mean for the project? What concepts were explored and with what priority?
- Was time a constraint and would more time have allowed for more achievements?
- How was the decision process: first approach the suppliers and then design from what was available? or design and then go to suppliers to see if they could produce the design?
- Did you manage to convince any client about changing their product to fit to the circularity requirements?
- How did the fact that you had to choose what was available inform the design?
- What were the most revolutionary or successful parts of circular economy thinking that impacted on the design?
- Where did all the products go after being dismantled?
- How much did BAM get involved in the project?

8.2.2. Services-specific

- What services were included in the building?
- How were the building services equipment sourced? Did you manage to return the products to their suppliers at the end of the project?
- IoT was a big part of the CE part of the building services strategy. When was it decided that information was important?
- What missing information in the material passport would you have included if you went back?
- Was the information gathered about products given back to the suppliers?

8.2.3. Findings and conclusions

- If you were to go back, would you change any decision taken on the project?

[5] Green Guide Standards: BRE's Green Guide to Specification examines the relative environmental impacts of commonly used construction materials and products (BRE, 2018)

- Circular buildings need more time to be procured than normal? E.g. Would adding 2 extra months to the process help to make it circular?
- How can you apply the flexibility that was needed to make this a circular building to a real commercial one? E.g. The fact that the availability of products drove the design or changed the size of the building.
- What needs to change in the industry for these circular concepts to be applied to commercial buildings?

8.3. Review of products and manufacturers

Table 16 enlists all products used in both projects mentioned in the report, including their manufacturers and a brief description.

Table 14. Products and manufacturers used in both buildings

Project	Product	Manufacturer	Description	More information
22 Gordon Street	Stella chilled beam units	Fläkt Woods (Fläkt Group)		www.flaktgroup.com Contact: Greg Clifford greg.clifford@flaktgroup.com
The Circular Building	Steel beams	Arcelor Mittal	Reused steel beams. The specific available sizes conformed the shape of the building	
	Timber cladding panels	Accoya		
	Cladding to structure clamps	Lindapter		
	MVHR unit	Arup	Open-source 3D printed unit	
	Duct work	Gatorduct	Highly sustainable cardboard duct sourced from managed forests	
	Saline battery	Aquion Energy/ Circuitree	C2C® certified, Aqueous Hybrid Ion (AHI™) technology made of non-toxic, abundant materials such as saltwater	
	'XIM' LED lamp	Xicato (2018b)	With run-time monitoring & storage capability. The entire module can be recycled. Lasts >50,000h with guaranteed colour & light output stability	
	Circular Lamps	Arup, Xicato	Low-energy bluetooth-enabled lamps controlled from an app. Reclaimed component include kilner jars. Designed to be dismantled and their component parts re-used.	
	Track spot lighting	Mike Stoane Lighting/ Arup	Simple design, efficient dissipation of heat, mechanical assembly fittings, & wireless light fitting control & sensing	
	LED profile	8 Point 3 LED	Remote phosphor light engine (the LED equivalent of a conventional lamp) allows replacement of installed fluorescent luminaires with efficient LEDs	
	Digital control	Tinkerforge, Raspberry Pi, NXP, Halcyon Microelectronics	Bluetooth low-energy wireless controls and 6LoWPAN communication (the technology behind IoT) to address each light fitting independently. The system is orchestrated by a Raspberry Pi processor: a consistent user interface for all the lights inside the building	
Other	Pay-per-lux LED lighting	Philips	Lighting as a service. Includes design and build, operation and maintenance of your lighting. Buy the light you use, instead of owning the equipment	www.lighting.philips.co.uk

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