

ISBU Modular Construction and Building Design Prototypes

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ISBU MODULAR CONSTRUCTION AND BUILDING DESIGN PROTOTYPES

By
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A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

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ABSTRACT

With the use of industrialised construction increasing, Buro Happold (BH) commissioned this research as part of on-going initiatives to address the lack of efficiency in design and construction. The research considers two major case studies where modularisation has been used to minimise complexity and increase standardisation. Referred to in this thesis as ‘*construction product prototypes*’ and ‘*building design prototypes*’, the two studies examine firstly the product development of an Intermodal Steel Building Unit (ISBU) used in multi-storey construction and secondly a modular station pre-design used and repeated on four station buildings. The ISBU is based on a standard ISO dry-freight container and its use in modular construction maximises the use of factory based off-site methods (OSM); this should improve consistency of product outcome with minimised impact on site. Very little academic work has been published on ISBU modular construction. The research therefore looks in detail at the process of ISBU modular product development and its engineering performance. It also compares production and procurement of the units on supplier-driven accommodation buildings in comparison to similar but non-modular client-led projects. Using multiple stages of project team interviews and project document analysis, the research data is coded, measured and analysed to describe the processes of product and design prototyping. The research demonstrates that the ISBU product was developed and refined through several major building projects and has reasonable engineering performance characteristics but may be more suited to temporary buildings. The principle of modular pre-designs as found in stations has benefits for rationalising the design process and simplifying and internalising complexities of construction. The research considers solutions for problems that are ill defined and a design process that is difficult to assimilate. This part of the research uses models for framing and problem/solution co-evolution to solve problems of ill definition and linear/non-linear design processes by building on Gero’s (1990) design prototyping theory model. Modularisation of the station designs was successful in reducing design effort and allowed a repeatable pre-design to be refined, but the design team struggled with the bespoke nature of the project designs. The comparison of case study data to models for manufacturing, procurement and design prototype development has led to a better understanding as to how these designs were achieved and how these same approaches could be applied in future.

KEY WORDS

Off-site Construction, Design, Prototyping, Product Development, Shipping Containers, Modularisation.

PREFACE

This research began in 2007 and was completed in 2016, in partial fulfilment of the requirements of the Engineering Doctorate (EngD) at the Centre for Innovative and Collaborative Engineering (CICE), Loughborough University. The research was conducted within an industry context and sponsored by Buro Happold Consulting Engineers.

The EngD is examined on the basis of this discourse, supported by five peer-reviewed publications. Presented within the appendices section of this thesis are four conference papers and one journal paper, all of which were authored by the candidate.

The main body of the text provides an in-depth overview of the work undertaken, the context, findings and implications for the sponsor and industry. Further details are explained within the papers included in the appendix section.

USED ACRONYMS / ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
ACSA	American Collegiate Society of Architects
AI	Artificial Intelligence
ARCOM	Association of Researchers in Construction Management
BAA	British Airports Authority
BIM	Building Information Modelling
CABE	Commission for Architecture and the Built Environment
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CIB	Conseil International du Bâtiment (now International Council for Research and Innovation in Building and Construction)
CIMC	China International Marine Containers Group Ltd.
CIRIA	Construction Industry Research and Information Association
CtO	Concept to Order
dB	Decibel Level
DD	Double Diamond Product Design Model
DEFRA	Department for Environment, Flood & Rural Affairs
DfMA	Design for Manufacture and Assembly
DtO	Design to Order
ER	Essential Requirement (see ETAG)
ECAM	Engineering Construction and Architectural Management
EOTA	European Organisation for Technical Approvals
ETAG	European Technical Approvals Guidelines
EtO	Engineer to Order
IBS	Industrialised Building Systems
ISBU	Intermodal Steel Building Unit
LCA	Life Cycle Assessment
LOR	Laing O'Rourke
MMC	Modern Methods of Construction
MtC	Make to Concept
MtF	Make to Forecast
MtO	Make to Order
NSSS	National Structural Steelwork Specification for Building Construction
ODPM	Office of the Deputy Prime Minister
OSM	Off-Site Manufacturing
UK	United Kingdom

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LIST OF PAPERS

During the course of this research the following papers, which are included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate.

PAPER 1 (SEE APPENDIX A)

Robinson, A.C., Swindells, T., (2012). Customised Container Architecture. Proceedings of the American Collegiate Society of Architects 2012 Fall Conference & Modular Building Institute Regional Institute Meeting. Offsite Theory & Practice of Architectural Production, September 27th - 29th, Philadelphia, Pennsylvania, USA.

PAPER 2 (SEE APPENDIX B)

Robinson, A.C., Wedge, J. Sauven, E., Swindells, A., Gibb, A.G.F., Austin, S.A., (2012). Embodied Carbon of Shipping Container Architecture based on an ISO Standard Platform. Proceedings of the Creative Construction Conference 2012, June 30th – July 3rd, Budapest, Hungary.

PAPER 3 (SEE APPENDIX C)

Robinson, A.C., Gibb, A.G.F., Austin, S.A., (2011). Efficiencies in design and manufacturing for construction using shipping containers. Proceedings of the 27th Annual ARCOM Conference, 2011, June 5th – 7th, Bristol, UK

PAPER 4 (SEE APPENDIX D)

Robinson, A.C., Gibb, A.G.F., Glass, J., Austin, S.A., (In review). Off-site Construction in Supplier-driven and Client-led Project Scenarios. International Journal of Construction Management.

PAPER 5 (SEE APPENDIX E)

Robinson, A.C., Gibb, A.G.F., Austin, S.A. 'Re-inventing the wheel?' – Case Study Research into Linear/Non-Linear & Framing Processes. Proceedings of the 29th Annual ARCOM Conference, 2013, September 2nd – 4th, Reading, UK

DEFINITIONS

Archetype - the original pattern or model from which copies are made; a prototype (OED 2016). Archetypes are the first and often singular examples of their type; each archetype may produce an analogue for a design (Gero 1990).

Carbon footprint – a measure of carbon emissions (OED 2016).

Client - a person using the services of a professional person or organisation (OED 2016).

Co-evolutionary - to deduce or develop jointly (OED 2016). In a co-evolutionary design, problem and solution emerge together (Poon & Maher 1997; Dorst & Cross 2001).

Construction - the action of framing, devising, or forming, by the putting together of parts for the erection of a building (OED 2016).

Customisation - the action or an act of creating or modifying something to meet a customer's individual specifications or requirements; modification of something to suit a particular person, situation, task, etc. (OED 2016).

Design - to make drawings for the construction or production of a device, product, etc. according to structural or functional criteria, sometimes without the implication of aesthetic requirements; to conceive, devise, plan (something immaterial, as a scheme, system, programme, etc.) (OED 2016).

Digital - a device, piece of equipment, etc., which uses digital technology. Of signals, information, or data: represented by a series of discrete values, typically for electronic storage or processing (OED 2016). Information technologies applied to construction are described as digital tools (Eastman & Sacks 2008; Lu & Korman 2010; Goulding et al 2012).

Discipline - a particular school or method of instruction; an educational philosophy. A branch of learning or knowledge; a field of study or expertise; a subject. Now also: a subcategory or element of a particular subject or field (OED 2016).

Evolve - to extract (something implicit or potential); to derive or deduce (a conclusion, law, or principle); to develop (an idea, theory, or system) (OED 2016).

Frame - see definition for construction. Also meaning to form or construct (a thought, a concept, an idea, etc.) in the mind; to conceive, imagine (OED 2016).

Industry - productive work, trade, or manufacturing carried out on a commercial basis, typically organized on a large scale and requiring the investment of capital (OED 2016).

Industrialisation - Production that makes use of equipment and technologies in order to improve production, reduce cost associated with manual labour (if this is what costs more) and consequently improve the quality of final product Warszawski (1999).

Industrialised Building Systems (IBS) – A combination of factory-based manufacturing with site based building. Industrialised construction combines off-site and on-site construction (Matt et al 2014).

Innovation - the action of innovating; the introduction of novelties; the alteration of what is established by the introduction of new elements or forms (OED 2016).

Manufacture - to make (a product, goods, etc.) from, (out) of raw material; to produce (goods) by physical labour, machinery, etc., especially on a large scale (OED 2016). In construction, manufacturing transforms raw materials into components and sub-assemblies to create final finished products (Winch 2003).

Mass customisation – tailoring standardised mass-produced products to meet customer needs. Economy of scale is through mass production of components and economy of scope is through modularisation (Pine 1999). In construction mass customised modularised components are pre-assembled for installation on site (Winch 2010).

Modular Construction – three-dimensional volumetric units that are generally fitted out in a factory and then delivered to site as the main structural elements of a building (Smith 2011; Lawson et al 2014).

Modular Design – the depiction of artefact variants based on a defined set of modules leading to reductions in complexity and reductions in cost (Meehan et al 2007).

Modules – functionally or structurally independent components that are clustered so that interactions are localised within each module and interactions between modules are minimised (Meehan et al 2007).

Multi-disciplinary Engineering (Spence et al 2001) - accommodating an understanding of different specialist engineering fields as well as an understanding of that engineering knowledge in the context of the social sciences and the humanities.

Off-site construction - also referred to as pre-fabrication and pre-assembly; a technique to improve quality and lower cost by maximising the efficiencies of manufacturing and minimising work on site (Gibb 2001).

Pre-assembly – with the aim of controlling the working environment, preassembly is the assembly of components into sub-assemblies, either off-site in a factory or on-site prior to final installation in place (Winch 2010).

Pre-design – a design for re-use (Lawson 2006; Anderson & Anderson 2007), using a set of concepts and common solutions for systematic variant design (Meehan et al 2007).

Production – the action or process of making goods from components or raw materials; the manufacture of goods for sale and consumption (OED 2016). In construction there are production strategies linked to materials flows, the initiation of manufacturing triggered by client payment and the amount of ‘pre-bid’ and ‘post-contract’ work carried out by the manufacturer (Winch 2003).

Prototype - a first full-size working version of a new vehicle, machine, etc., of which further improvements may be made; a preliminary version made in small numbers for evaluation, or from which improved or modified versions may be developed (OED 2016). A prototype is an approximation of one or more dimensions of interest in a product (Ulrich & Eppinger 2008), including concept sketches, mathematical models, simulations and test components as well as functioning pre-production models. Design prototypes describe a cognitive view of function and structure used in a process model of design (Gero 1996); a set of potential concepts that are retrieved to consider for a new project.

Stereotype - something continued or constantly repeated without change (OED 2016). Mass production is a form of stereotyping (Gero 1996).

Standardisation – the use of standard components or modules. In construction the aim of standardisation is to increase numbers of identical elements so that economies of scale can be achieved, moving production more towards mass or lean methods. The limiting factor is the extent of market; and conception may limit the amount of elements that can be standardised (Winch 2010).

1 BACKGROUND TO THE RESEARCH

1.1 INTRODUCTION

In common with most research in construction this research work investigates how the construction industry can be more efficient, with this thesis approaching the issue from a design practice perspective. Specifically, it focuses on construction product development and design theory. There are two parts to the research, linked through the common theme of modularisation (Meehan et al 2007). The first part considers the development of dry-freight containers as Intermodal Steel Building Units (ISBU 2012) for modular construction (Smith 2011; Lawson et al 2014). The research describes the product's technical development, its commercial application to multi-storey hotel buildings and concludes on its strengths and weaknesses as a construction product. The second part of the research considers a set of case study buildings based on modular (Meehan et al 2007) pre-designs (Lawson 2006). The buildings are bespoke railway stations with building layouts based on a set of modular elements.

Both sets of case studies ultimately help to refine a theoretical model for increasing design optimisation. The first set of projects have standard designs with well defined briefs. The second set of projects have non-standard designs based on ill defined briefs. Design prototyping theory (Gero 1996) can be applied to both types of outcome and provides a range of different design situations. This approach, which rationalises the use of products and pre-designs (Lawson 2006) could help optimise future design processes that are currently quite irregular.

This thesis uses the term ‘prototyping’ in two ways. While product prototyping is commonly associated with the physical testing of pre-production models in product development processes, Ulrich & Eppinger (2008) also describe concept sketches, mathematical models, simulations and test components as prototypes (Ulrich & Eppinger 2008). Therefore a prototype can be a non-tangible analytical model and a conceptually drawn representation of a product as well as a physical model. In the first case study, *prototyping* is used to describe the generation of a pre-production models or ‘*construction product prototypes*’. In the second case study, the processes for pre-designs are termed ‘*building design prototypes*’ (Gero 1996).

The doctoral thesis is in six chapters and the research has been realised through a series of four published conference proceedings and one journal paper (see Appendices A to E),

This first chapter continues by explaining the links between context, the sponsor’s role, aims and objectives, study work packages, and justifications for the research.

1.2 RESEARCH CONTEXT

For at least 70 years (Murray & Langford 2003) there have been attempts through policy change to address concerns in UK construction performance, in particular its high costs and low efficiency (Egan 1998; Latham 1994; Morton & Ross 2002; Wolstenholme et al 2009; Cabinet Office 2011). The debate on industrialisation is focusing again (Cabinet Office 2011) on supply chain policy, with parts of the construction sector promoting benefits of off-site construction (Buildoffsite 2015). The growing influence of manufacturing and more widespread availability of digital tools has provided new opportunities, but this has also led to further complexities in understanding how construction can become more efficient (Morton & Ross 2002; Bachman 2004; Smith 2011).

1.2.1 HISTORY OF MODULAR CONSTRUCTION AND OFF-SITE SYSTEMS

Building off-site is a construction method that has existed for at least 2000 years (Gibb 1999) with evidence of Roman pre-fabricated fort building in the UK, and off-site timber cruck building in 12th century Britain (O'Neill & Organ 2016). More recent instances of pre-assembly can be traced back to the Crimean War of the 1850's with Brunel's field hospital (Gibb 1999). Between 1945 & 1949, 150,000 prefabricated steel and concrete houses were built in the UK, with the ARCON system by Taylor Woodrow being the most widely adopted (Woudhuysen & Abley 2004). In the 1960's, precast concrete technology was at its zenith in post war Europe with French systems by Raymond Camus, and Larsen and Nielsen from Denmark. The most widely adopted concrete housing manufacturer in the UK in the 1960's was the Bison system by Concrete Ltd.

Off-site construction has had a particular impact on design and construction of schools and hospitals in the UK. 'CLASP', the Consortium of Local Authorities Special Programme emerged in 1957 (Russell 1981), based on previous light steel school building projects for West Sussex County Council in 1936 was inspired by Bauhaus principles of Walter Gropius. The development of the CLASP system was not pre-planned but came about through a collaboration of several local authorities and the adoption of a supplier's solution as standard. Its origins can be traced to a light prefabricated classroom for Middlesex County in 1943. This was followed in 1947 by a programme of buildings using the Hills Patent Glazing Company 'Presweld' system for Hertfordshire local authority, which then led to the first prototype 'CLASP' building (Russell 1981). See Figure 1.1.

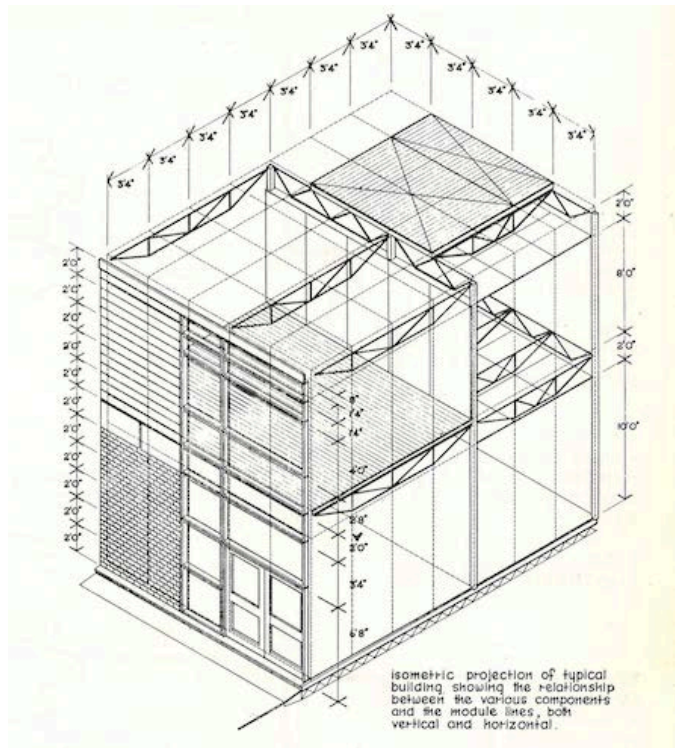


Figure 1.1 Isometric of CLASP system for classroom module (source: Russell 1981)

Modular construction (Smith 2010; Lawson et al 2014) is an advanced form of off-site construction offering the highest levels of preassembly (CIRIA 1999). The principle of modularisation is to cluster and isolate complexities and variants in order to reduce costs and simplify interfaces between elements (Meehan et al 2007). Modular construction allows for at least 70% of a building to be completed before arriving on site (Smith 2010; Lawson et al 2014). This form of construction is particularly popular when there are constraints on construction process and site logistics (Lawson et al 2014).

Having begun its use in residential buildings and more recently in larger temporary and permanent structures (Smith 2011 or 2012), modular construction is available in timber, steel and concrete. Three-dimensional volumetric units are used in multi-storey buildings for social housing, student accommodation, commercial buildings, health care, schools and hotels

(Lawson et al 2014). Light steel modules are widely used for this type of construction and precast concrete modules are chosen in some cases for their high robustness, although 2D concrete panel construction is more widespread than 3D concrete volumetric construction.

There have been a number of significant projects including tall buildings using modular construction. In the US, a 21 storey San Antonio Hilton with 496 precast concrete modules was completed in 1968 (Smith 2011). This project was preceded by Habitat'67, a residential complex built around the time of the Montreal World Exhibition. Moshe Safdie's design for a rambling complex of 184 interconnected apartment buildings was built from 354 concrete modules (Habitat'67 2016). Figures 1.2 to 1.3 show the open-sided wall units of the large development being lowered into position.



Figure 1.2 & 1.3 Precast modular construction for Habitat'67 (source: Moshe Safdie archive www.habitat67.com)

Three years later, Japanese architect Kisho Kurokawa had started his design of the first steel modular tower. See Figures 1.4 and 1.5. Nakagin Tower's 140 capsules are all bolted to two 11 and 13 storey high stair towers. The mainly steel towers were partially encased in concrete. Each module can be independently removed/replaced but none have been removed or added since the tower was first completed in 1972 (MoreAEDesign 2016).

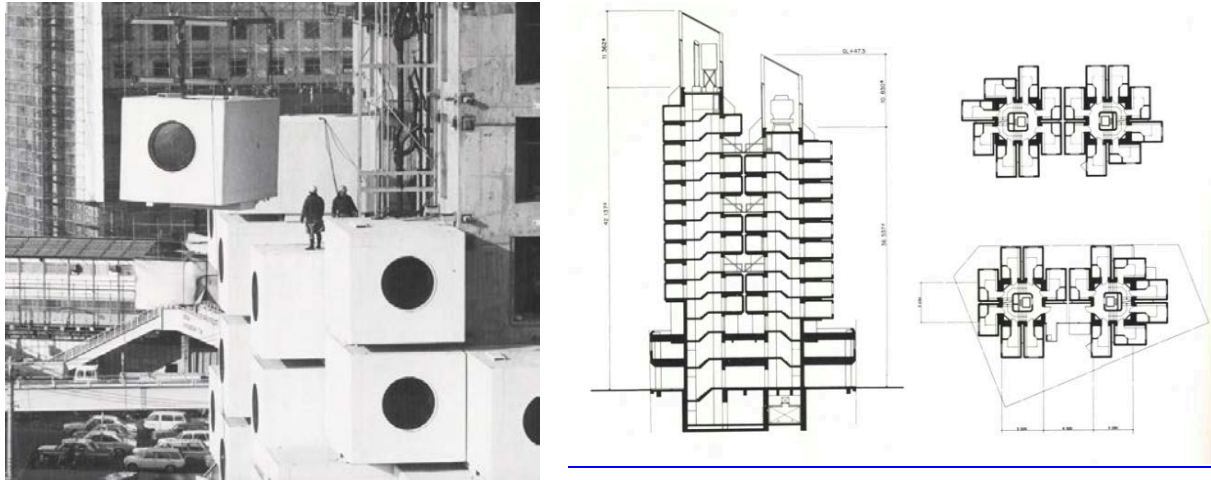


Figure 1.4 & 1.5 Steel modular construction for Nakagin Tower (source: MoreAEDesign.com)

Around 2000, the use of light steel modular construction began to increase in the UK (Lawson et al 2014). In 1999, the Murray Grove development for the Peabody Trust in London by manufacturer Yorkon and architect Cartwright Pickard raised the bar in terms of architectural modular building production. See Figure 1.6. The incorporation of the 80 modular units into an L-shaped building design drew the attention of the wider public to the possibilities of a contemporary building aesthetic for modular building in the UK. Prior to that time modular construction (Smith 2011; Lawson et al 2014) had been more widely associated with portable temporary buildings.



Figure 1.6 Murray Grove development for Peabody Trust (source: Cartwright Pickard)

Modular light steel exists in three forms: modular room units with closed supporting side walls, non-load bearing modular bathrooms/kitchens, and structurally framed modules with removable non-load bearing side walls for larger open-plan spaces (Gorgolewski et al 2001). Light steel, timber and concrete modular have since been used on schools, hospitals, offices, supermarkets, and further high-rise residential. In 2010, 805 light steel modules were used to build two student residential towers up to 24 storeys high in Wolverhampton. See Figures 1.7 and 1.8. In the US, also in 2010, Atlantic Yards, a 30,000m², 32-storey tower was being built involving the manufacture of 930 modules to provide 350 apartments (Smith 2010).



Figure 1.7 & 1.8 Wolverhampton student residential tower (source: Building.co.uk)

1.2.2 PRE-DESIGNS & BUILDING DESIGN PROTOTYPING

Design practices have a role in improving construction through standardisation and are drawn to modularisation (Smith 2011). The challenges for designers are to introduce these approaches while also addressing individual client needs that are sometimes complex and ill defined (Cross 2006). Engineer to order (EtO) scenarios (Briscoe & Dainty 2005; Smith 2010), being client-led (Winch 2003) can sometimes be in conflict with the manufacturing industry approach to construction that is more supplier-driven (van Nederveen et al 2010).

In this research, pre-designs (Lawson 2006) are proposed as a way of overcoming limits posed by client-led projects, leading to the current consideration of building design prototypes (Gero 1996). The ISBU module is an example of a supplier-driven construction product offered after construction product prototyping has taken place. In design practice, a building design prototype is the first of many designs in an iterative practice linked to manufacturing (Smith 2012). Design prototypes are based on concept models with the wider use of the term

prototype used in design practice to denote a design or concept suitable for repetition. The usefulness of building design prototypes is in being able to envisage a potential design with only a small amount of situational information (Gero 1990).

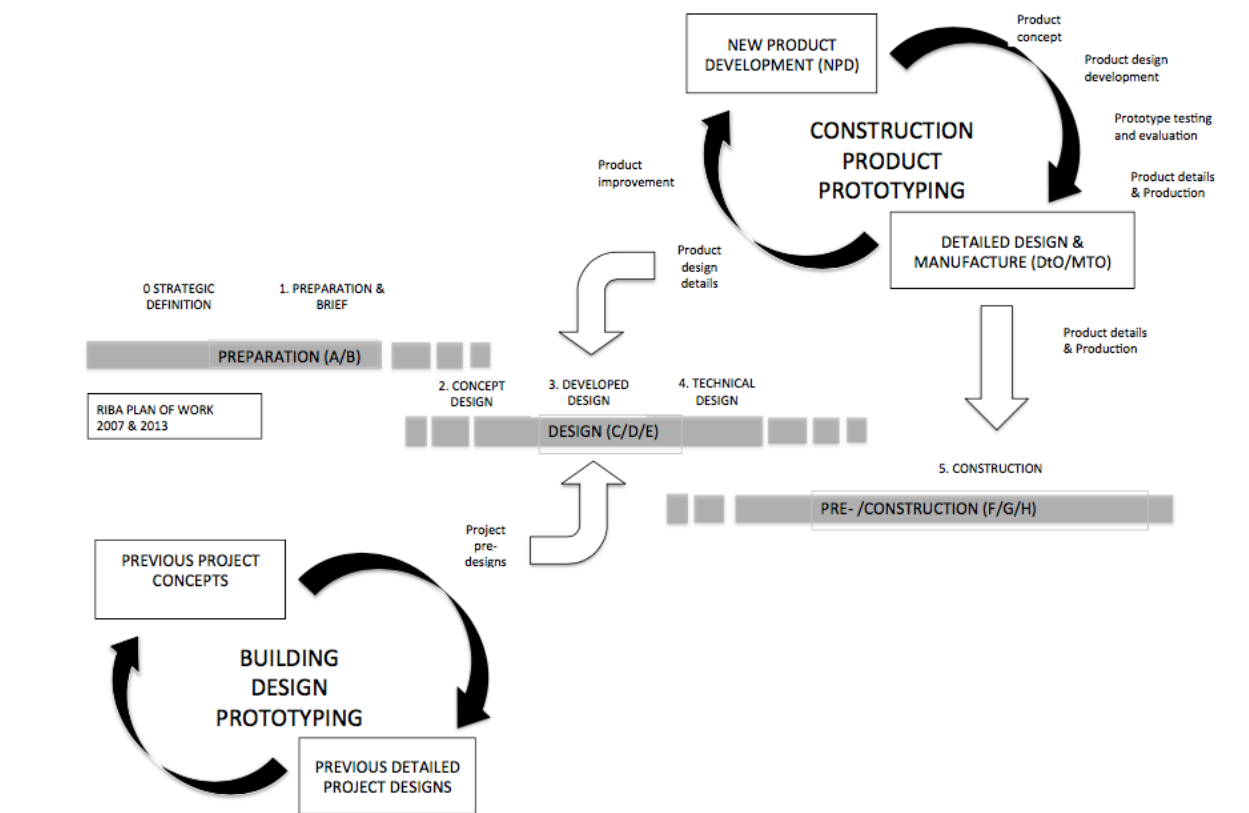


Figure 1.9 Corresponding roles of construction product prototyping and building design prototyping against a generalised RIBA Plan of Work (source: author based on RIBA 2007/2013)

To demonstrate more clearly the relationships between *construction product prototyping* (Ulrich & Eppinger 2008) and *building design prototyping* (Gero 1990) Figure 1.9 shows them in the context of a standard plan of work (RIBA 2007/2013). Whether procurement is ‘traditional’ client-led (Winch 2003) or design & build, a similar sequence is followed, albeit with certain cross-overs between phases of designing, pre- and post-construction; an approximated sequence is therefore shown in the figure.

1.3 THE INDUSTRIAL SPONSOR

1.3.1 AN INTERNATIONAL MULTIPLE DISCIPLINARY PRACTICE

The topics of modular construction (Smith 2010; Lawson et al 2014) and building design prototyping (Gero 1990) are of considerable interest to the project sponsors Buro Happold. A multi-disciplinary practice founded in 1976, Buro Happold has grown in scope and size during the last 40 years. Under the multi-disciplinary umbrella of building engineering, the practice combines design services for different scales of project in civil, structural and building services engineering, with additional expertise offered in acoustics, fire engineering, façade engineering and other specialist areas. The firm now employs over 1000 staff worldwide, within 23 offices in Europe, North America, Middle East, Africa and the Asia Pacific. In 2013 the practice turnover was £116m, with an operating profit of £12.9m.

Much of its commercial success is attributed to its ability to tackle multidisciplinary designs using well-integrated teams, and for this it relies significantly on the interdisciplinary design skills of those engineers involved. The practice aspires to promote education and training through the design process (Schön 1983) and uses design reviews and ‘project close-out’ meetings to reinforce learning from projects. After Action Reviews (AAR’s) (Morrison and Meliza 1999) and other hindsight processes (Bartholomew 2008) can increase an awareness of tacit knowledge, which can be applied to future work. In 1999 the practice employed this approach within a co-located design and construction team for the Millennium Dome (now the O₂ Arena) project as shown in Figure 1.9. A building of significant scale and technical complexity, the design relied significantly on modularisation and off site construction. Buro Happold was given the MacRobert Award for its novel integrated engineering solution.



Figure 1.9 Millennium Dome (source O₂) and Figure 1.10 London Olympic Stadium (source: Balfour Beatty)

Using a similar learning-in-practice approach (Schön 1983) Buro Happold played an important role with Balfour Beatty in the planning, design and construction of the London 2012 Olympic Park, including the 80,000 capacity main stadium (Buro Happold 2014). See Figure 1.10.

The practice actively engaged with early initiatives for boosting supply chain construction through Constructing Excellence (2005), which followed the Movement for Innovation (M4i 2009). Between 1994 and 2000 Buro Happold were involved in demonstration projects and developed buildings based on a building product for the British Airports Authority (BAA) client in partnership with consultants 3DReid and contractor Laing (later becoming Laing O'Rourke - LOR). The buildings involved standard pre-designs and modularisation of components over successive projects leading to economies of production. BAA reported savings in their five office building designs between 1994-1999 of 12.4%, based on 1994 figures for capital costs (BAA 1999). This series of projects also led to some improved practice knowledge research in prefabrication (Roynon 2004). The office product later became the subject of a study by Loughborough University on the viability of pre-configured adaptable buildings (Gibb et al 2007).

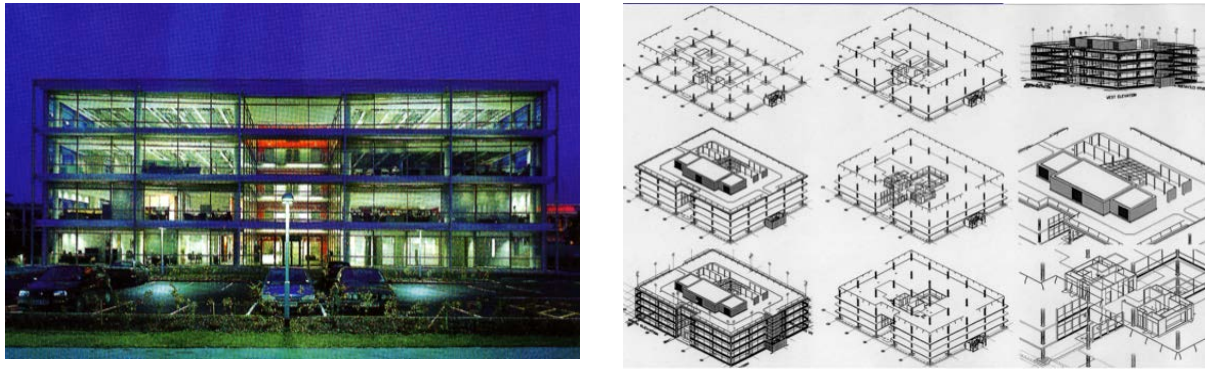


Figure 1.11 & 1.12 BAA Office Product (source: BAA Lynton)

1.3.2 CONTAINERISED CONSTRUCTION PROJECTS

In 2003 Buro Happold embarked on a practice initiative to increase their research and development on design standardisation and industrialised construction. Having previously worked on innovative modular buildings, BH provided engineering support to a building based on shipping containers (Container City 2002) for Urban Space Management: see Figure 1.13. The building was made from recycled ISO (International Standard Organisation) containers, and later in 2003, BH collaborated with contractor George & Harding (G&H) on a purpose-made volumetric modular construction (Smith 2010; Lawson et al 2014) system based on a similar shipping container product. Referred to in literature as an Intermodal Steel Building Unit or 'ISBU' (ISBU 2012), the principles of this product and its use in hotel buildings are the subject of the first research area of this thesis.

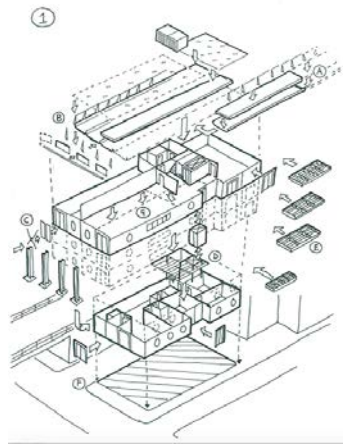


Figure 1.13 & Figure 1.14 Container City by Urban Space Management (source: Buro Happold)

Shipping containers are sometimes openly shown as elements of architecture, as was the case with Container City. However, for the more recent use of ISBUs, the containers were concealed in the final building. Being over-clad in conventional façade materials to disguise their origins, seven projects using this technique were built in the UK between 2006 and 2009 leading to 1000 en-suite hotel bedrooms being manufactured in China. See Figure 1.15.



Figure 1.15 Verbus Container System (source: Buro Happold)

The same product development team also worked on a standardised modular hotel building product for an air carrier client. The project required low-cost hotels that were demountable for re-use, and this made the ISBU a desirable option for their design, although this was never taken forward to construction. The container manufacturer CIMC, who purchased the ISBU design by Buro Happold/G&H in 2011, still produces modular building products using ISBUs (CIMC 2014).

1.3.3 MODULAR STATION PROJECTS BASED ON PRE-DESIGNS

Given their previous experiences of applying pre-designs (Lawson 2006) and modularisation (Meehan et al 2007) to building products, Buro Happold looked to apply similar principles to achieve design savings on other projects. The station buildings for Haramain High Speed

Railway in Saudi Arabia were projects where greater efficiencies could be made possible through a more systematic approach to the design process. Involving around 100 project engineers and technicians, and a total design team of around 200 including architects and sub-consultants, this project was double the size of either the Millennium Dome or Olympic Park teams, and is still one of the largest single projects attempted by Buro Happold. The stations had many repeated elements in their designs, and it seemed feasible to consider a repeatable modular design solution.



Figure 1.16 & Figure 1.17 Haramain High Speed Rail, Saudi Arabia (source: Foster & Partners)

Working in a joint venture with the architects Norman Foster & Partners, it was decided to create a co-located office with 50 engineers and architects in a single location to work on a modular design, with satellite teams in regional offices working on the station designs following those pre-designs. The modular team's role was to develop a building design prototype to be taken up by the station design teams working in the other offices. The prototyped designs were created using parametric CAD models. The success of this strategy was later assessed through After Action Reviews (AAR) (Morrison and Meliza 1999) and interviews. The conclusions from that project closeout review and the subsequent 27 interviews with design team members forms the case studies for the second research area of this doctoral thesis.

1.4 AIMS AND OBJECTIVES

1.4.1 RESEARCH AIMS

Taking into consideration these recent attempts to address challenges of efficiency through construction product development and design rationalisation, the aims of this research are two-fold:

1. To investigate the ISBU product as developed for multi-storey modular construction (Smith 2010; Lawson et al 2014).
2. To refine design prototyping theory (Gero 1996) on building pre-designs (Lawson 2016), particularly when briefs are ill defined.

To meet the aims of research on product development of the ISBU module, the following research objectives have been chosen.

- i) To establish the scope of research on ISBU modular product development.
- ii) To describe the technical development of the ISBU module through building design projects.
- iii) To identify the production and procurement strategies for the ISBU modular construction (Smith 2010; Lawson et al 2014) using a theoretical framework of a supplier-driven (van Nederveen et al 2010) solution for multi-storey hotel buildings and comparing similar, but client-led hotel buildings using non-modular solutions.
- iv) To establish construction product prototyping processes (Ulrich & Eppinger 2008), engineering performance, and production/procurement scenarios (Winch 2003) for the ISBU modules used in multi-storey construction.

To meet the aims for refining a theoretical model for building design prototyping (Gero 1990) through the modular station pre-designs (Lawson 2006), the following objectives have been chosen.

- i) To establish the scope of ill definition (Cross 2006) in the client's brief and its resolution through framing (Schön 1983; Paton & Dorst 2011).
- ii) To identify instances of problem/solution co-evolution (Poon & Maher 1997; Dorst & Cross 2001) in the design process.
- iii) To establish how linear (Pugh 1990; Cross 1990) and non-linear (Lawson 1994) design processes were applied using the modular (Meehan et al 2006) pre-designs (Lawson 2006).
- iv) To determine instances in the design process that are aligned with building design prototyping theory (Gero 1990).
- v) To make recommendations for the future application of design prototyping theory (Gero 1990) to building.

1.5 ACHIEVEMENT OF OBJECTIVES THROUGH WORK PACKAGES

These research objectives are achieved through work packages (WP's 1-4) mapped out in Figure 1.11, and summarised in Table 1.

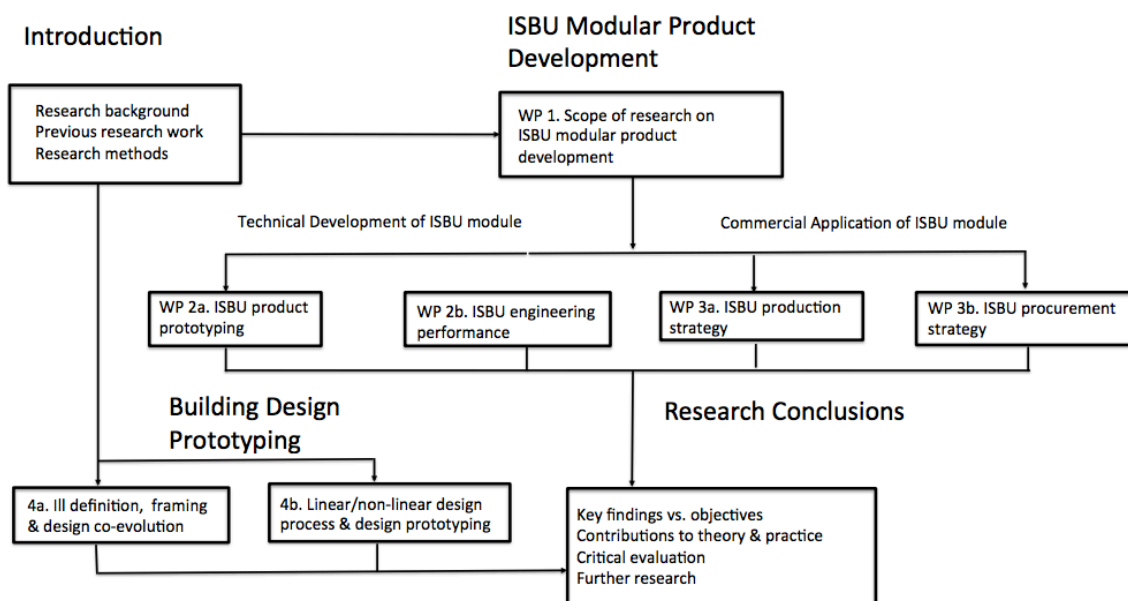


Figure 1.11 Mapping of research work packages

Objective	Topic	Research Data Source	Research Methods	Papers
WP 1	Scope of research for ISBU modular product development.	First stage interviews (12).	Qualitative interpretation of interview data.	1 & 2
WP 2a	ISBU construction product prototyping.	5 Case Studies Project documentation	Qualitative interpretation of interview data and product documentation.	1, 2 & 3
WP 2b	ISBU engineering performance.	Second stage interviews with engineers involved in product development (3).	Quantitative measurement of engineering data.	
WP 3a	ISBU production strategies.	Project documentation for 3 additional case studies with interviews (3).	Quantitative measurement of technical data.	3 & 4
WP 3b	ISBU procurement strategies		Qualitative interpretation of interview data and product documentation.	
WP 4a	Ill definition, solution framing and	Case study data, project	Qualitative interview research	5

	problem/solution co-evolution	reviews, team interviews		
WP 4b	Investigation into linear/non-linear design processes, and building design prototyping.	(27).		

Table 1.1 Work packages mapped against research data, methods and publications

1.5.1 SCOPE OF RESEARCH ISBU MODULAR PRODUCT DEVELOPMENT (WP 1)

Through the introductory papers (Papers 1 & 2) and data analysis in the thesis, the research explains the origins of the ISBU based on dry-freight shipping containers leading to the development of the current modular construction product (Smith 2010; Lawson et al 2014). The research begins with analysis of open interviews with the product development team and the coding of this data shaping the following research. The data reveals that the technical development of the product, its market application and commercialisation are the dominant themes of discussions; this leads to a detailed investigation of the product's development, engineering performance, production and procurement.

1.5.2 ISBU TECHNICAL PRODUCT DEVELOPMENT (WP 2)

The research uses project data from specification documents, reports, meeting minutes and drawings for five case studies to determine the stages in ISBU prototype development and engineering performance characteristics including carbon footprint as outlined in Papers 1, 2 and 3.

1.5.3 COMMERCIAL APPLICATION OF ISBU MODULE (WP 2B)

Paper 3 defines levels of preassembly (Gibb 1999) and models for manufacturing (Winch 2003). Using those classifications for off-site construction, and production and procurement strategies, the project data from the five ISBU case study projects were used to determine a progression of their product development. In paper 4 the standard modular room unit is measured using levels of preassembly and this is compared with standard non-modular rooms from three hotel buildings of a similar typology, but using alternative construction methods. In this research a method of graphical representation is developed and this is used to demonstrate the degree of off-site and on-site construction for comparison of procurement strategies in the following work.

The research then seeks to compare project conditions for supplier-driven designs with different levels of preassembly. To clarify the arguments for and against a supplier-driven design approach the research evidences those trends in recent projects through project team interviews and compares data on the ISBU projects with the other hotel buildings which are more client-led.

1.5.4 BUILDING DESIGN PROTOTYPING (WP 4)

In common with many building project briefs, the station projects are ill defined, and so the research compares the brief development process with framing (Schön 1983; Paton & Dorst 2011) which is a process for clarifying ill defined briefs as outlined in Paper 5. In addition, interview data taken from the project interviews for the modular station designs is used to determine instances of problem/solution co-evolution (Poon & Maher 1997; Dorst & Cross 2001).

Paper 5 also describes standard design theories for linear (Pugh 1990; Cross 2006) and non-linear (Lawson 1994) problem solving strategies to align with well defined and ill defined problem solving. The case study research continues by examining those linear (Pugh 1990; Cross 2006) and non-linear (Lawson 1994) design processes on the four rail station designs based on the single modular pre-design. Using project documents and project interview data the research determines the success of the pre-design (Lawson 2006) in its potential to eliminate unnecessary redesign. The findings are then used to refine design prototyping theory (Gero 1990) for further application to buildings.

1.6 JUSTIFICATION FOR THE RESEARCH

1.6.1 ADDRESSING PERCEPTIONS OF STEP-CHANGE

Recent literature has shown a more evolved approach to the question of manufacturing and its role in improving construction performance (Koskela 2000; Fernández-Solís 2008; Winch 2010; Nadim & Goulding 2011; Nadim et al 2014; Vibaek 2014). A similar perspective is being adopted for this research in reviewing current models for manufacturing in construction and to seek a methodology that addresses the contradictory needs of client and manufacturer through an informed design approach.

1.6.2 ISBU MODULAR PRODUCT DEVELOPMENT

ISBUs are a unique building product originating from a different industry sector and very little academic work has been published in this area before. Although more popular in the self-build and temporary construction sectors, containerised construction has not reached mainstream building to the extent that other methods and materials have done.

This research fills gaps in academic literature by exploring the specific application of ISBUs to large-scale permanent accommodation using modular construction (Smith 2010; Lawson et al 2014). The product development process through the first projects demonstrate the challenges of prototyping (Ulrich & Eppinger 2008) a product originating from the transportation sector, pre-configured for a different use other than building.

1.6.3 PRODUCTION AND PROCUREMENT MODELS FOR ISBU CONSTRUCTION

Due to the growing research interest in supplier-driven initiatives (Wolstenholme et al 2009; van Nederveen et al 2010; Cabinet Office 2014), these case studies compare ISBU products with similar projects that are more client-led (Winch 2003; van Nederveen et al 2010). Recent literature continues to indicate that supplier-driven designs are linked to increasing degrees of off-site construction. The research therefore assesses the degree of off-site by measuring levels of preassembly (Sparksman et al 1999; Gibb & Pendlebury 2006), and to do this in a consistent way it combines metrics from several sources for off-site methods with a metric for on-site construction. A graphical representation of levels of preassembly allows the extent and type of off-site to be more quickly assimilated, with the objective of clarifying and comparing production and procurement strategies and a greater understanding of the project circumstances for supplier-driven designs.

1.6.4 DESIGN THEORIES ON CO-EVOLUTION AND DESIGN PROTOTYPING

Given that design projects are often ill defined and that there is a need for greater standardisation in designs, the research uses co-evolutionary theory (Poon & Maher 1997; Dorst & Cross 2001) and design prototyping (Gero 1996) as ways to clarify the use of pre-designs (Lawson 2006). This could lead to further research on design optimisation.

1.7 STRUCTURE OF THESIS

The following four further chapters of this thesis are described below.

Chapter 2 examines existing literature on construction policy and performance, definitions of off-site construction, modular construction, product development and design standardisation.

Chapter 3 describes the research design. It sets out the epistemic perspective and ontological thinking as well as the research approach and research methods.

Chapter 4 summarises the analysis of the ISBU data in the work packages WP 1-3.

Chapter 5 summarises the analysis of the building design prototype data in WP 4.

Chapter 6 summarises the research findings, proposes refined theory models and concludes on their applications to practice and future academic work.

2 PREVIOUS WORK

2.1 INTRODUCTION

The research work begins with a review of the economic importance of the construction sector and recent government reports aimed at improving its efficiency. There are many challenges ahead for construction, and industrialisation seems to be an on-going and important part of transitional step change in the industry, but how this can best be applied still remains unsolved. Most notably there is a lack of alignment between the needs of clients (Harper 1990; Wolstenholme et al 2009) and those of manufacturers (Winch 2003). The possible role of the design practice in being able to reduce some of this lack of alignment is therefore of interest.

The research is investigating the potential to be found in the construction product development of containers and their application to construction, as well as the potential for greater design standardisation; the literature therefore explores academic areas relevant to these two fields of research. To understand the context of construction product development, the research considers previous studies on off-site construction (Gibb 1999), modular construction (Smith 2010; Lawson et al 2014), and the engineering performance characteristics of modules. To understand the context of the container module as applied to construction, the research looks at previous work on manufacturing models for construction, including production and procurement strategies. To understand design standardisation better, the research looks at theory models, co-evolutionary development (Poon & Maher 1997; Dorst & Cross 2001) of ill defined problems/solutions, framing/reframing (Schön 1983; Atkin 1993; Paton & Dorst 2011), linear/non-linear design theory (Pugh 1990; Cross 2006; Lawson 1994) and models for design prototyping (Gero 1996).

2.1.1 CONSTRUCTION INDUSTRY ECONOMICS AND POLICY

In the UK, construction accounts for around half of all public and private capital expenditure, and 12% of total national expenditure. In 2012 it contributed £83 billion in economic output, 6% of the total GVA (Gross Value Added). It employed 2.15 million people or 6.5% of the total workforce in 2013 (Rhodes 2014). However, productivity has been poor compared to other sectors; a situation that policy makers have been attempting to address for many decades (Murray & Langford 2003; Morton & Ross 2002). Like many industries, construction output is very dependent on economic conditions (Rhodes 2014) but seems more adversely affected than other sectors. UK studies show that the percentage fall in construction output during 2008-2012 was much greater than the change in output for the economy as a whole, and its output by 2014 had still not recovered to pre-2008 levels.

The 1984 Latham report – ‘Constructing the team’ - anticipated a 30% reduction in costs by 2000 by standardising contracts and revising tender methods and urged government to take the lead in improving links between design and construction. Similarly, the ‘Rethinking Construction’ report by Egan (1998) went even further in advocating a total change in industry culture, with a shift in focus towards the client, using increasingly integrated teams and processes, with better quality control. The M4i – ‘Movement for innovation’ (M4i 2009) – intended that all public sector clients would be Egan compliant (Morton & Ross 2008).

However, following the economic recession of 2008, the Wolstenholme report (2009) quantified the lack of progress with the Latham and Egan reforms. The construction industry

had reached the end of a period of demonstration projects in the ‘Continuous Improvement’ programme (Smyth 2010), and although these showed some improvements in performance, their outcomes were not representative of construction practices across the industry. Overall, the targets for step-change set by Egan had not been met (Wolstenholme et al 2009; Cabinet Office 2011). To quote Egan, there has been “...too little change, too narrowly adopted and at too slow a rate” (Wolstenholme et al 2009. p8).

2.1.2 MAJOR CHALLENGES FOR CONSTRUCTION

Construction efficiency through greater industrialisation is therefore often an important priority for the UK and other governments (Egan 1998; Latham 1994; LeBeau & Viñals 2003; Wolstenholme et al 2009; Cabinet Office 2011). Enhancements to building performance have been selective; changes in building services and building envelope are most notable during the last 30 years (Jaggar & Morton 2003; Bachman 2004). During the last 15 years there has also been a concerted effort to encourage greater use of off-site construction methods (Buildoffsite 2015) as a way of taking inefficient site operations into a factory environment.

Since the mid eighteenth century, the built environment has become increasingly influenced by industrialisation (Banham 1980; Frampton 1995; Pawley 1990) and since the late twentieth century it has been further influenced by information technologies (Bachman 2004). Few would disagree that advanced technologies and manufacturing techniques are making many other industrial sectors more effective (Smith 2011), and some of these improvements have started to be translated to construction (Volk et al 2014). However, both in the UK and internationally, the take-up of more industrialised methods in construction is low (LeBeau & Viñals 2003), despite a willingness by many to consider such techniques (Steinhardt et al

2014). Construction productivity in the US since the 1960's, as measured in terms of labour costs against gross construction product, has fallen by over 10% while manufacturing sector productivity has doubled in the same period (Smith 2011).

In the UK there has been much discussion of the figures (Taylor 2010), but there is a general consensus that off-site construction accounts for around 2 to 5% of overall construction output (Goodier & Gibb 2005, Taylor 2010, Research Markets 2012; Goulding et al 2013). Reasons cited for similarly poor levels in EU countries have been attributed to past poor performance, cost and productivity issues (Nadim & Goulding 2011). However, increasing specialisation and industry fragmentation are also cited as barriers to improved industrialised methods (Nawi et al 2014).

Off-site with its savings through standardisation and longer-term supply chain partners boosted by advances in mechanisation, material and digital technologies is still widely seen to be a route to step-change in the construction industry (ODPM 2013). Most would agree that an increase in manufacturing not only reduces waste and improves quality, but also allows construction outcomes to become more predictable (Egan 1989; Wolstenholme et al 2009).

However, with the exception of housing and some commercial lettings, the majority of buildings in the UK are one-of-a-kind, site-linked projects (Morton & Ross 2002). In these situations it is harder to apply the principles of pre-planned, controlled, factory-based manufacturing methods directly (Koskela 2000; Fernández-Solís 2008) and construction has always contained an element of on-site work (Vibæk 2014). Nevertheless, there are still some aspects of construction that could be more productive through greater industrialisation

both off-site and on-site, leading to attempts through construction policy to improve levels of industrialised methods in construction.

2.1.3 POLICY RESEARCH FOR IMPROVING CONSTRUCTION

Policy and much construction research states that the industry needs to become more like manufacturing (Egan 1998, Gibb 2001; Arif & Egbu 2010; Nadim 2012). The manufacturing sector has been very successful in harnessing digital technologies to enhance and integrate design and manufacturing processes. It is hoped that improved digital tools for Computer Aided Design (CAD) (Cabinet Office 2011), using Building Information Modelling (BIM) (Eastman & Sacks 2008; Lu & Korman 2010; Goulding et al 2012) will similarly improve the industry. However, progress has been slow due to the divisive nature of the industry (Nawi et al 2014). Lack of education and training has also contributed to the construction industry's fragmented and compartmentalised organisational structures, which are exacerbated by economic boom and recession cycles (Jaggar & Morton 2003; Woudhuysen & Abley 2004; Bailey et al 2015).

Although previous research (Latham 1994; Morton & Ross 2002) has identified poor infrastructure through low investment as a main cause of inefficiencies, the industry is also hindered by conflicts of interest related to the short-term perspectives of the commercial market; namely awards to lowest-cost tenders leading to highly confrontational contractual relationships (Latham 1994; Wolstenholme et al 2009). These and many other issues linked to negative procurement practices have been raised consistently in government reports since the early part of 20th century (Morton & Ross 2002; Murray & Langford 2003). A boost in supply chains and industrialised manufacturing are seen as ways of solving some of these long-term structural issues in the industry (Egan 1998; Wolstenholme et al 2009), particularly

with the potential for step-change through the use of more industrialised methods with a supplier-driven approach (van Nederveen et al 2010). However, the anticipated and much talked about trends for increased use of manufacturing across the whole industry (Egan 1998; Gibb 1999, 2001; Gann 2000; Gibb & Isack 2003; Goodier & Gibb 2005; Blismas et al 2006; Arif & Egbu 2010) have not yet materialised.

Much effort has been focused on industrialisation but a continued lack of progress suggests that the industry does not yet have a complete understanding of how manufacturing can assist design and construction. Notably there is a lack of alignment between the needs of clients (Harper 1990; Wolstenholme et al 2009) and those of manufacturers (Winch 2003).

2.1.4 CONTRIBUTIONS FROM DESIGN PROFESSIONALS

The role of design professionals has not been explored extensively (Groak 2002), and with such widespread concern for construction performance (Murray & Langford 2003; Ashworth & Hogg 2014), further studies are needed on how design practice can improve construction.

Research on the consultant's contribution to off-site methods (Goodier & Gibb 2005; Blismas et al 2006; Pan et al 2004, 2007) suggests that design professionals impede innovation through ignorance and a lack of detailed knowledge of construction methods (Pasquire et al 2002; Goulding et al 2012) and can be obstructive to the changes that innovative practices such as off-site offer (Wolstenholme et al 2009, Vernikos et al 2012).

However, professionals have argued that choices for buildings are made not only on the basis of standards of economy and function (Fox et al 2002; Emmitt & Gorse 2005; Nadim & Goulding 2011) but also on the basis of human needs (Brand 1995; Lusby-Taylor et al 2004;

Till 2009). While the construction supply chain is focused on functional and technical matters, design is concerned with wider social, aesthetic and ethical issues in addition to the practicalities of construction (Frampton 1995; Ching 2010), with these sometimes overriding drivers for greater building economies. In many cases projects are unique, with design briefs that are ill defined (Cross 2006). Construction practice is therefore seen as paradoxical, because it is driven by both control and variability (Fernández-Solís 2008). However, some have also observed that designers work to a limited number of stereotypes with many designs tending to follow similar processes (Adkin 1993), and therefore rationalisation should be possible.

Faced with such conflicting drivers, some design professionals have introduced pre-designs and pre-configured solutions (Lawson 2006; Anderson & Anderson 2007; Ching 2010; Smith 2011). Manufacturers have also offered standard and customised products (Gibb 1999; Groak 2002; Kieran & Timberlake 2003; Smith 2011) but these do not yet appear to have addressed all issues of client individuality as previously mentioned.

This debate on industrialisation and design optimisation therefore needs a renewed perspective when applied to construction (Fernández-Solís 2008). Clients are seeking unique solutions to their unique problems. Manufacturers and contractors are seeking to standardise products to maximise their operational efficiencies and designers are at best mediating between these two drivers (Groak 2002). Product developers have successfully used product prototyping as a way of formalising a design process and rationalising a product outcome (Ulrich 2003) and modularisation is a design approach that isolates complexities (Meehan et al 2007). Design prototyping of pre-configured solutions could be another means to

rationalising building solutions and making them more attuned to manufacturing. The challenges with construction are the circumstances of building, which do not always suit a product-led solution, but by using pre-designs that can be applied more universally for improved conceptual development, this could address client-led issues of individualisation and at the same time improve construction product performance. This would also lead to a minimisation of unnecessary re-designs, and optimise the potential for industrialisation through off-site methods.

2.2 OFF-SITE CONSTRUCTION

There are many terms used to describe building processes that start off-site and in a factory. Historically ‘prefabrication’ has been used widely (Anderson & Anderson 2007; Smith 2011), but more recent terms include ‘modern methods of construction’ (MMC) (Lusby-Taylor et al 2004; Pan & Goodier 2011; Nadim 2012), off-site manufacturing (OSM) (BURA 2005), off-site production (OSP) (Nadim & Goulding 2010), ‘standardisation and preassembly’ (Gibb & Pendlebury 2006), ‘modular construction’ (Smith 2010; Lawson et al 2014), ‘mass customisation’ (Pine 1999) and ‘design for manufacture and assembly’ (DfMA) (Boothroyd 1994). These terms are defined in greater detail in the following sections.

2.2.1 OFF-SITE MANUFACTURING (OSM) AND OFF-SITE PRODUCTION (OSP)

OSM and OSP are similar and interchangeable, production being the process of manufacturing. OSM can improve quality and productivity through an integrated supply chain (Stirling 2003) and can be applied to frames, panels and volumetric units. These methods are particularly appropriate for bathroom, bedroom and kitchen pod assemblies.

However, key suppliers need to be involved early in the design process (Gibb 1999) with contractors being involved through multi-stage design and build tenders. 97% of correspondents in a recent survey agreed that reasons for adopting OSP (Nadim & Goulding 2010) were time reduction, quality and reduction of accidents on site, and ‘adding value’ through OSP is achieved through increased certainty of deadlines, waste reduction and improved environmental performance. However, OSP cannot be implemented by a single organisation and there are inhibiting factors related to inflexible designs, transportation and limited market demand (Nadim & Goulding 2010).

2.2.2 MODERN METHODS OF CONSTRUCTION (MMC)

MMC has been applied specifically for housing (Goodier & Gibb 2005), but is also seen as a grouping term for a more economic process using a number of methods including off-site (Nadim 2012). The Home Builders Federation has described MMC as an “efficient product management process” that includes ‘prefabrication’, off-site production (OSP), and off-site manufacturing (OSM). MMC goes beyond OSM by including services, foundations, walls, and materials (BURA 2005). The “Barker 33 Cross Industry Group” (Barker 2004) defined MMC as focusing on better products and processes through improvements in business efficiency, quality, customer satisfaction, environmental performance, sustainability and the predictability of delivery timescales. MMC therefore is similar to off-site, but more broadly based than a particular focus on product, engaging with people through better delivery and construction performance.

To clarify MMC further, BURA (2005) defined OSM as: 1) panel system, 2) volumetric, 3) hybrid (semi-volumetric), and 4) sub-assemblies and components. Non-OSM comprises: 1)

tunnel form, and 2) thin joint masonry. Alongside these definitions, previous concerns for MMC were raised concerning poor sound proofing, lack of thermal mass, longevity and durability of MMC as well as the possibilities of systematic failures (BURA 2005). The Barker review also identified that “at the present time, traditional brick and block methods of construction remain cheaper, in many cases than modern methods of construction” (Barker 2004; p 113). However, it is argued by others that the full potential of off-site products is not always being evaluated (Blismas et al 2006) and that the material, labour and transportation costs do not reflect full savings. For example, reduction in site facilities, craneage and snagging are not easily valued as well as ‘softer’ savings in H&S, management and process which are rarely included (Blismas et al 2006).

2.2.3 STANDARDISATION AND PREASSEMBLY

Standardisation and preassembly are assumed characteristics of off-site (Gibb, 1999; Winch 2012), with both standardisation (number of identical or similar parts) and preassembly (levels or degree of fabrication off-site) being measurable (CIRIA 1999).

The benefits of standardisation are linked to value for money through repetition leading to savings in time and cost, improved quality, and certainty of outcome. In construction early involvement of manufacturers leads to a minimisation of time on site and possibly earlier project completion if built into an overall strategy for maximising the benefits of off-site methods (CIRIA 1999; Gibb 1999; Buildoffsite 2015).

Defining the elements in construction that can be standardised, and estimating how much assembly needs to take place off-site and on-site leads to a classification of levels of

preassembly. Several similar level of preassembly have been proposed which are summarised below:

0. Raw and processed materials for site intensive construction
 1. Component manufacture – small scale manufactured items or ‘loose parts’ for site intensive construction
 2. Elemental sub-assemblies and planar systems – factory assembly of components (semi-finished elements), structural panels and wall panels.
 3. Volumetric 3D modular construction – factory built units made from sub-assemblies enclosing space (prefabricated/integrated elements)
 4. Complete buildings – systems of modular components providing a completed building
- After Gibb (1999), CIB (2010) and Lawson et al (2014).

The images in Figure 2.1 show graphically three of these preassembly types: elemental sub-assembly, 2D planar assembly and 3D volumetric modular construction.



Figure 2.1 a) Elemental sub-assembly, b) planar and c) volumetric building methods (source: Buro Happold)

Standard panelised 2D preassembly methods and volumetric 3D modular construction (Gibb 1999) offer the greatest opportunities for combining integrated processes off-site (Smith 2011; Lawson et al 2014). The use of the term ‘modular’ is accurate because the

construction method clusters together technical solutions with common characteristics into a product structure (Paton & Dorst 2011). In a well-integrated modular product solution, the internal complexity, which is more integrated remains largely unchanged from project to project with repeat work focused on the external interfaces (Meehan et al 2007).

2.2.4 MASS CUSTOMISATION AND DFMA

Mass customisation (Pine 1999) is the modifying of a product to meet a customer's individual specifications or requirements and DfMA is an approach for improving manufacturing through the design process (Boothroyd 1994). The way that design is used to improve the outcomes of construction through product development is covered in later sections of this chapter.

2.3 SHIPPING CONTAINERS AND THE ISBU

The development of ISBU module is preceded by a brief introduction to the ISO dry bulk container.

2.3.1 PRODUCT CHARACTERISTICS OF THE DRY FREIGHT CONTAINER

Dry freight 'Series 1' (ISO 668) containers are the most widely manufactured products using the International Standards Organisation (ISO) container platform. As described in Paper 1, they are a mass customised product alongside other types of products adopting the dimensions, fixings and stacking characteristics defined by the ISO standards. The container is used widely in the transportation industry and is described as being 'intermodal', having a standard sizes and fittings (see Figure 2.2) transferable between different modes of transport. This has made the container a central product in an automated system for delivering goods

worldwide with minimum delay due to the decrease in time for loading and unloading compared to traditional bulk freight methods (Levinson 2006).

Units are made from high grade (S355) weathering steel to dimensions defined by ISO 668. The most common dimensions are 8ft (2.4m) wide, 8½ ft. (2.6 m) high and 20 or 40 ft. (6.1 or 12.2 m) long. Tolerances of +0 and -5 mm (width) and -10 mm in length are permitted. Taller and longer units up to 50ft are also available.

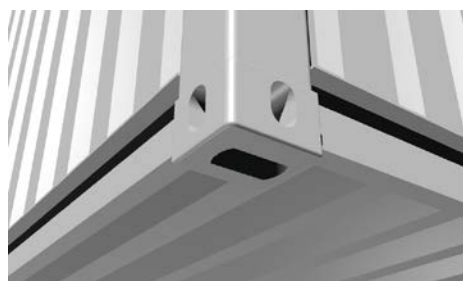
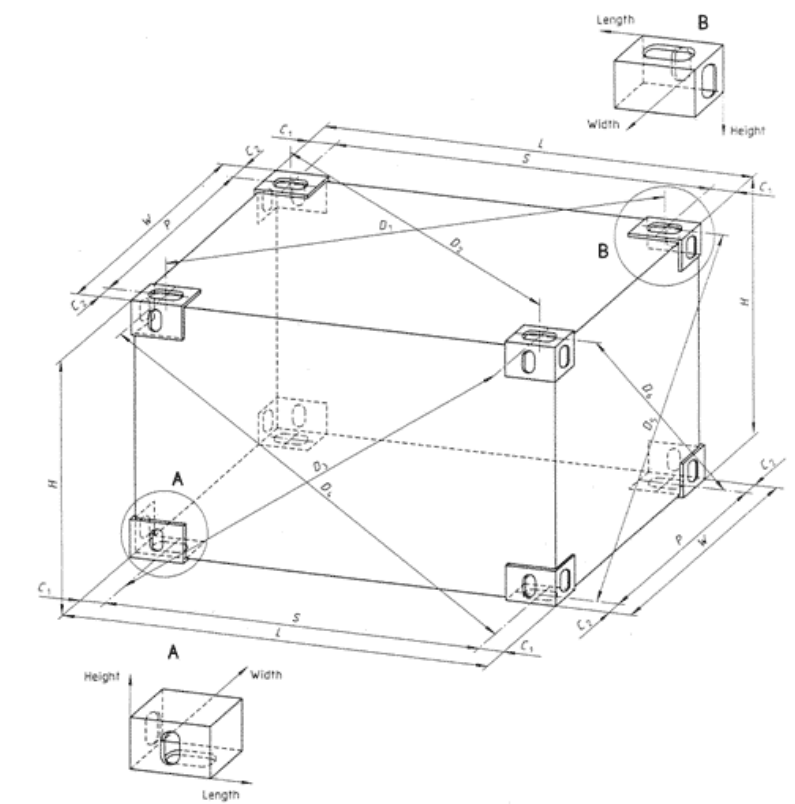


Figure 2.2 Shipping container corner casting for locating and coupling units using a universal self-locking system (source: Verbus)

The most critical dimensions for the container are those that give the positions of the corner fittings. These are defined with limited tolerances to coordinate with all the infrastructure use in intermodal transportation. See Figure 2.3.



<u>Position of Corner Fillings and Diagonal Dimensional Tolerances (mm)</u> (source Tandemloc)				
<u>Container Type</u>	<u>Length S</u>	<u>Width P</u>	<u>Diagonal Tolerances</u>	
			<u>D1-D2 or D3-D4</u>	<u>D5-D6</u>
<u>40 ft. (1A) (30 T gross)</u>	<u>11985</u>	<u>2259</u>	<u>19</u>	<u>10</u>
<u>20 ft. (1C) (24 T gross)</u>	<u>5853</u>	<u>2259</u>	<u>13</u>	<u>10</u>

Figure 2.3 Standard corner fitting locations to ISO 668: 2013 (source: www.tandemloc.com)

Containers are load tested to ISO 1496-1:1990 as shown in Figure 2.4, so that they can be safely lifted and stacked on ships. Standard load tests for a 20ft container using a hydraulic loading frame apply a 864 kN on each corner post, a lateral racking load of 152.4 kN and a longitudinal racking load of 76.2 kN (Containex 2013).



Figure 2.4 Load testing of prototype container (source: Verbus)

2.3.2 INTERMODAL STEEL BUILDING UNIT (ISBU) MODULES

Paper 1 (Appendix A) in this thesis describes how containers are used in construction, the economic arguments for their use, and therefore attractiveness for repeat-order building developers. The paper also describes instances of their application to permanent and semi-permanent buildings, particularly in the residential and hotel sector, including case studies where the detailed data has been used for this research.

An imbalance of trade between producers and consumers had resulted in a surplus of steel units in many ports for several decades, leading to containers being re-used for different purposes including habitation. The dimensions of the standard unit do not easily suit building use, hence the need to modify a standard freight container.

The development of an oversized container was a key differentiator for this new product in competition other ISBU products on the market, and was protected by a patent in the UK and other selected countries (UK Patent No. 0324363.1). Having established that it would be

possible to transport an oversized unit by ship and road, while still using conventional container infrastructure, the consortium believed that this could be a significant innovation on the standard ISBU which either provides very narrow rooms or provides wider rooms by arranging two units with open sides. The need to open up the sides of the unit, it was believed, was a significant barrier to being able to complete fully finished units off-site in the factory.

The need to modify the container has led to the development of an over-sized modular product based on the container platform. Figure 2.5 is a graphic of the Verbus container adopted for multi-storey building construction. The unit is based on an extended 20 ft or 40ft dry freight container design with steel frame and corrugated infill panels. Added to the inside of the units are layers of insulation, plywood and plasterboard (not shown). Externally the units have multiple corner fittings, bolt boxes for vertical and horizontal connections and steel plates for fixing of external cladding. The unit typically includes a built-in riser to connect floor to floor between units.

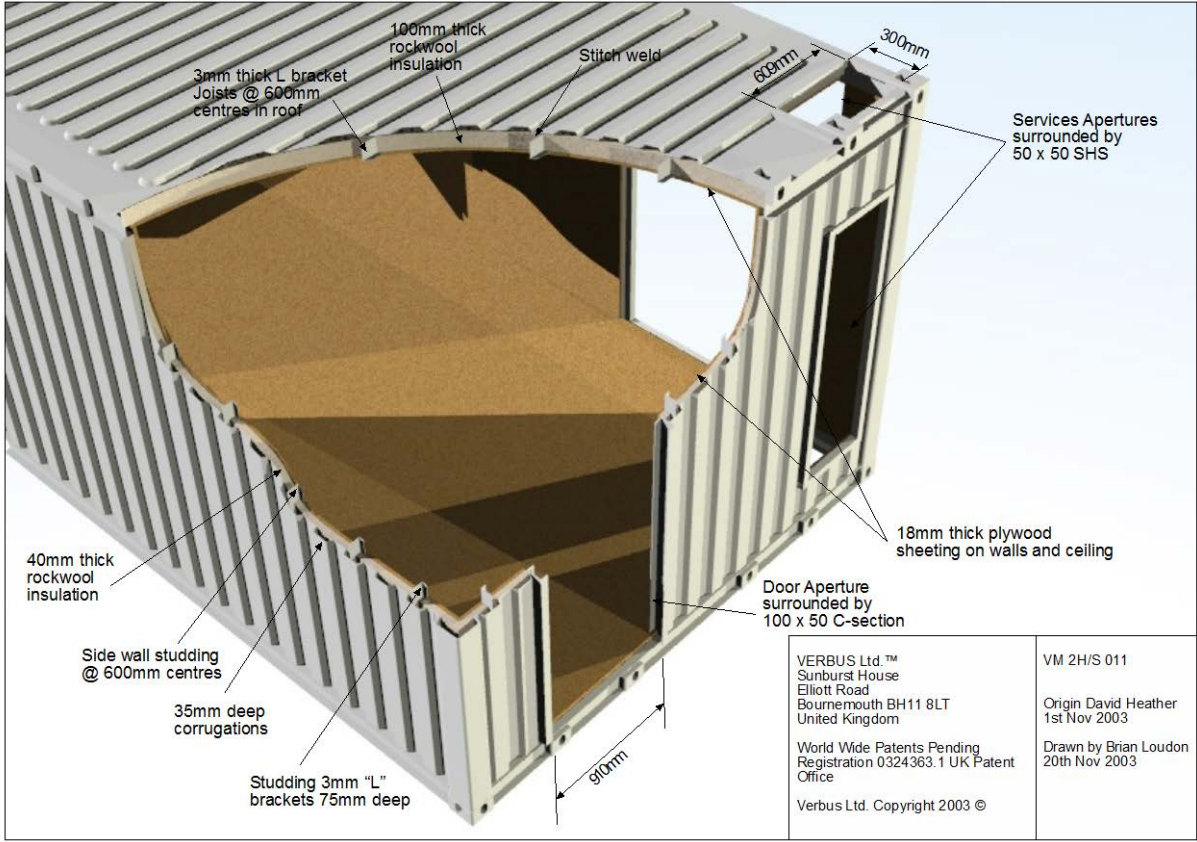
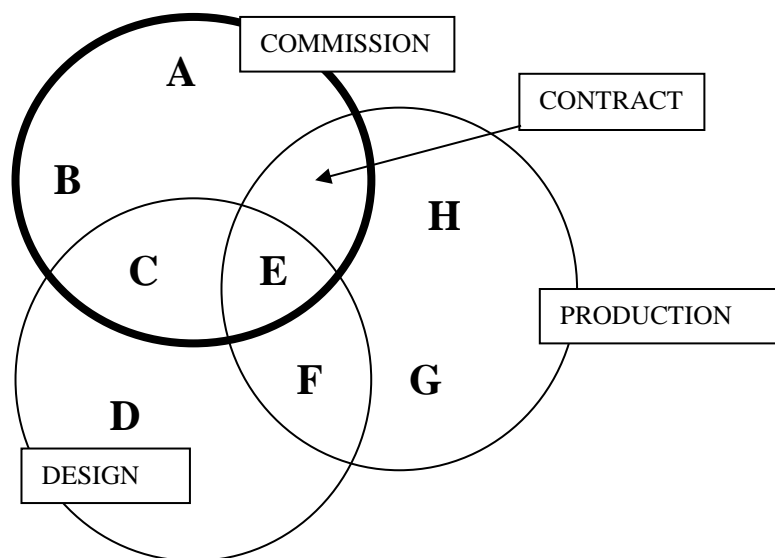


Figure 2.5 Cut away of single bedroom module with vertical riser, 1.6 mm steel outer skin, 75 to 100 mm deep steel studs and joists, insulation and inner plywood lining.

2.4 PREVIOUS MODELS FOR CONSTRUCTION PRACTICE

Construction practice has also been described as a cyclical non-linear process (Harper 1990; Groak 1992; Fernández-Solís 2008), and Harper offers a loose structure for this as shown in Figure 2.6. Construction factors in the Harper model are grouped under linked main phases of “Commission”, “Design” and “Production”. Into these terms are placed: site, basic decisions (brief), volumes, environment, function, production methods, materials, components and services.



A = Site Exploration, B = Basic Decisions , C = Spaces, D = Environment, E = Functions, F = Materials, G = Components & Services, H = Production Methods.

Figure 2.6 Model for construction practices (Harper 1990)

Others have similarly defined these or similar phases in greater detail. Emmitt (2002) describes key factors for a project brief or commission as being: the client's needs, legislation, environmental effects, time constraints, cost, and buildability. Emmitt & Gorse (2005) also define the overall performance of a design by: space requirements, thermal and acoustic performance, sustainability, fire and material properties, design and service life, use, quality and appearance. Similarly, factors in production include: availability of labour and materials, sequence of construction and tolerances, reduction of waste (labour, materials and time), protection from the weather, integration of structure, fabric and services, maintenance and replacement, disassembly and recycling strategies (Emmitt & Gorse 2005).

2.4.1 MODELS OF MANUFACTURING

Some have observed (Winch 2003) that the process of building is closer to complex systems production than volume manufacturing. Building elements are rarely made to forecast and their manufacture happens on a mostly 'pull' basis, that is, designed and built following a

client’s commission (Winch 2003). This means they cannot be easily improved by process re-engineering (Winch 2003). Nevertheless, Winch (2003) and others have identified generic production strategies, which are described in more detail in Paper 3. These include concept to order (CtO), design to order (DtO) or make to order (MtO) and make to forecast (MtF). CtO is used in traditional procurement; MtF or ‘make to stock’ is the ideal production scenario for a product, although rarely achieved in construction. DtO/MtO are production strategies for mass customisation (Pine 1998; Kieran & Timberlake 2003). Winch (2003) groups these generic production strategies into production information and material flows as shown in Figure 2.7.

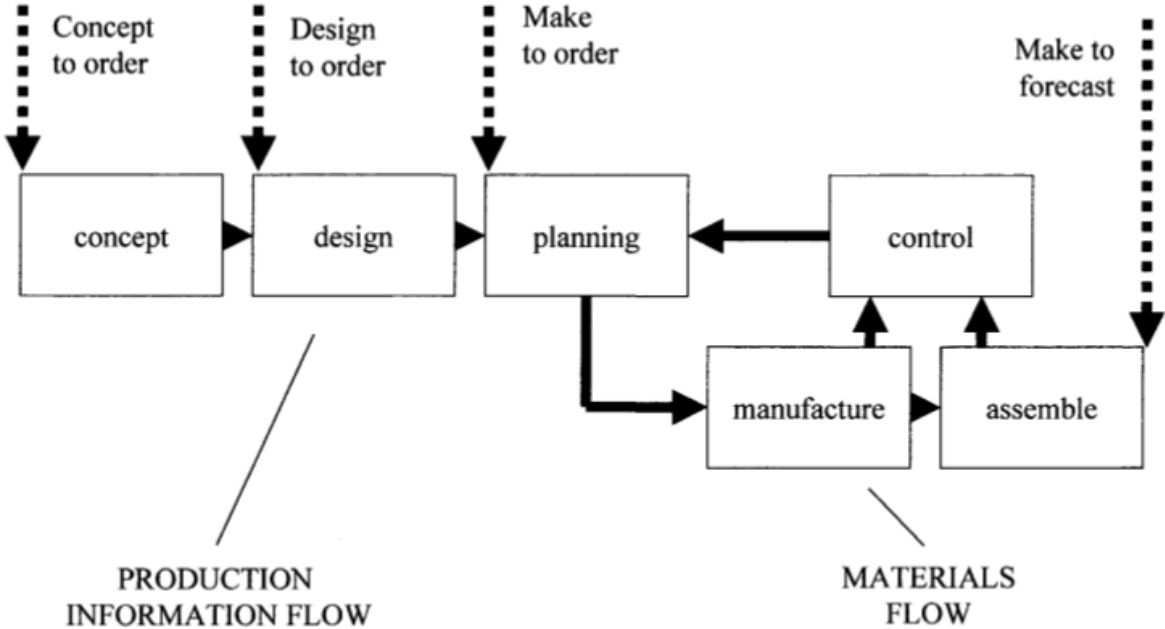


Figure 2.7 Production strategies and information flows (Winch 2003)

The strategies for commissioning, design and production are useful for describing project scenarios, but before developing them further in the research the next sections will describe procurement models.

2.4.2 PROCUREMENT MODELS

Both Winch and researchers at TU Delft identify three distinct types of procurement for producing a building: 1) 'Traditional', 2) 'Design Build' or 'Tender' (Winch 2003), and 3) 'Product Development' (Winch 2003; van Nederveen et al 2010). Terms used by Delft in Figure 2.8 augment the second procurement type as DBFMO (Design, Build, Finance, Manage & Operate) and the third type as LBC (Living Building Concept), but the overall sense is the same as Winch's (2003) 'Production Processes' that are set out in Table 1 in Paper 3 (Appendix C). An important assumption of the TU Delft research is that supplier-driven designs based on product development are more likely to have standard components and preassemblies. They also assert that a traditionally procured project will have the least amount of standardisation and a tendered design and build project is somewhere between these two outcomes. Traditional procurement is 'top-down' i.e. client-led, and supplier-driven procurement is 'bottom-up'.

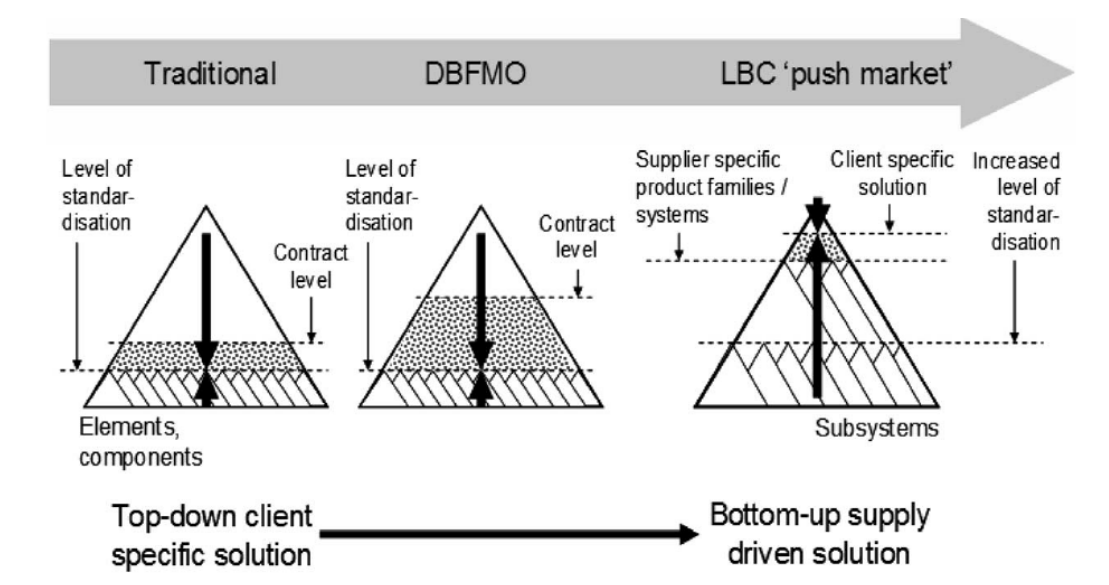


Figure 2.8 Building procurement and degrees of standardisation (van Nederveen et al 2010, p 242)

It is this relationship between client and manufacturer involvement, types of contract and levels of standardisation with its use of sub-systems that seems to be the key to understanding how and when projects are more industrialised and are made off-site using pre-assemblies, sub-assemblies and components.

2.5 DESIGN THEORY MODELS AND DESIGN PROTOTYPING

2.5.1 DESIGN THEORY MODELS

There are many different models for design to explain the convergent/divergent processes. These tend to include phases of conjecture, synthesis and analysis (Pugh 1990; Cross 2006; Lawson 2004, 2006) and there appear to be two types of project brief: ‘tame’ and ‘ill defined’ (Cross 2006).

Well defined problems that are routine and ‘specification driven’ (Winch 2010) are likely to be tame and therefore solved through incremental adaptation. Ill defined projects are by nature unsolvable through a linear method (Pugh 1990; Cross 2006) because there is too much data to analyse and synthesise; designers instead rely on conjecture and analysis (Cross 2004, 2006) to develop a solution. Therefore, the degree to which a brief is defined indicates whether the design is routine or creative (Gero 1996) and uses predominantly synthesis or conjecture.

Ill defined problems are common in construction (Schön 1983) and, due to their ill definition (Cross 2006), briefs need to be ‘framed’ (Schön 1983; Atkin 1993). Framing presents each building design as a mental model defining size, layout, architecture etc. that becomes a reference point for further development of ideas (Atkin 1993). Framing defines boundaries

and situations and is used as a way of describing generic perspectives (Schön 1983; Atkin 1993), leading to framing also being used in establishing building types.

In product development the brief is clearly defined prior to production, but there is still a process of divergent and convergent thinking. This has been most usefully described through the double diamond (DD) model (Design Council 2005). The DD model has four distinct stages: 'discover', 'define', 'develop' and 'deliver' as indicated in Figure 2.9.

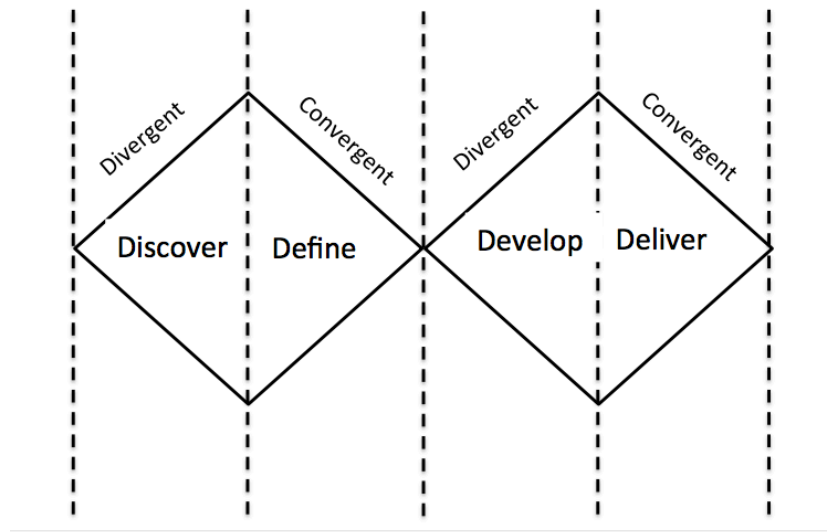


Figure 2.9 Divergent/convergent design model (Design Council 2005)

A construction product could follow this process, and if a building product supplier is able to define the market, it is reasonable to anticipate that their product development could also follow these stages. However, not all construction outcomes can be so clearly defined. When the project brief is ill defined and the process innovative or creative, the definition phase will not be so well resolved. The diagram in Figure 2.10 is proposed as an equivalent of the DD model for ill-defined briefs based with more loosely defined problems and solutions (Dorst & Cross 2001).

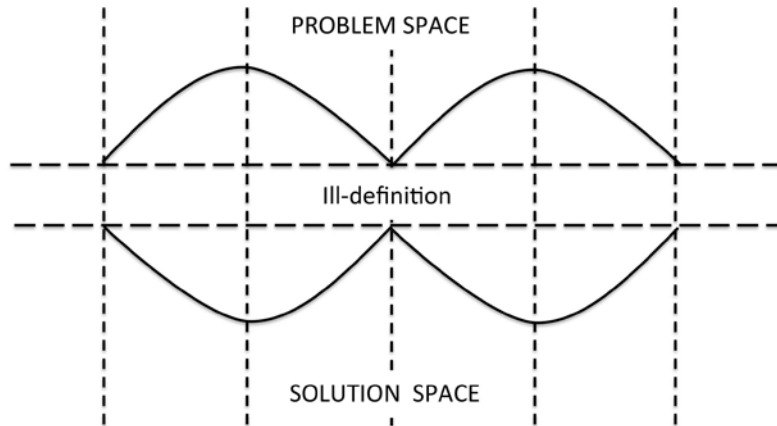


Figure 2.10 Ill defined model

(By author, based on Design Council 2005, Schön 1983; Dorst & Cross 2001)

Since the space between the lines in the DD diagram represents the degree of project definition, the separation in the second diagram indicates the lack of resolution at stages in the design and production process. Some have observed that ill definition (Cross 2006) remains because there is an on-going dialogue between the problem and the solution (Dorst & Cross 2001). Poon & Maher (1997) have expressed this ill definition and on-going dialogue as a co-evolutionary relationship. The design exists in the problem and solutions spaces, and these are mutable through ‘Focus’ and ‘Fitness’, but also to some extent autonomous in their development as indicated in Figure 2.11.

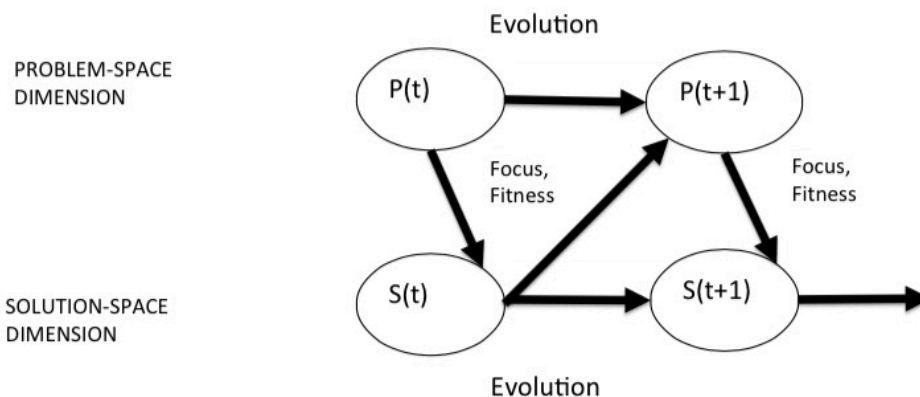
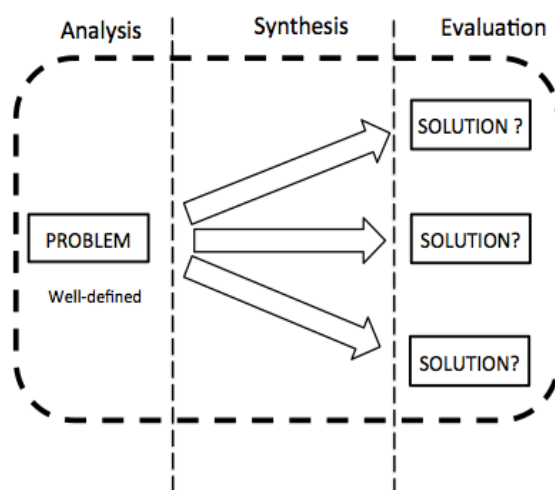


Figure 2.11 Co-evolutionary design for ill defined problems & solutions
(Poon & Maher 1997)

This co-evolutionary theory model is used for Artificial Intelligence (AI) and in industries such as software design where sudden changes in design commission and product outcome are expected. Co-evolutionary models describe the design as episodes, rather than a continuous process. The development of problem and solution can benefit from previous schemas to create a partial structuring of ideas. As a result, a designer's background and expertise (Dorst & Cross 2001) when working in a co-evolutionary process, may have more influence on those creative outcomes than in more routine project circumstances.

2.5.2 LINEAR/NON-LINEAR DESIGN PROCESSES AND DESIGN PROTOTYPING

It is well known that designers work from their individual design experiences using generalised concepts or schemas (Lawson 2006). Routine & non-routine designs (Gero 1996), also referred to as typical and innovative (Dorst & Cross 2001), are differing design approaches. In Paper 5, these routine and non-routine design processes are compared to linear and non-linear designs. Diagrams from the paper are included in Figures 2.12 and 2.13.



Linear
(Pugh 1990; Cross 1990)

Figure 2.12 Linear problem solving (source: by author based on Pugh (1990) & Cross (2006))

For well defined problems, a linear process with cycles of analysis, synthesis and evaluation, (Pugh 1990, Cross 2006), is the most common model. In complex designs several competing solutions are investigated (Harper 1990), and an objective assimilation of the options is used to find the best solution (Figure 2.12).

If problems are ill defined, designers tend to use a more conjectural process: a cyclical non-linear model with problem structuring and problem solving (Lawson 1994), using a primary generator and testing process as shown in Figure 2.13. The primary generator or ‘proto form’ is a way of short-circuiting an otherwise complex activity.

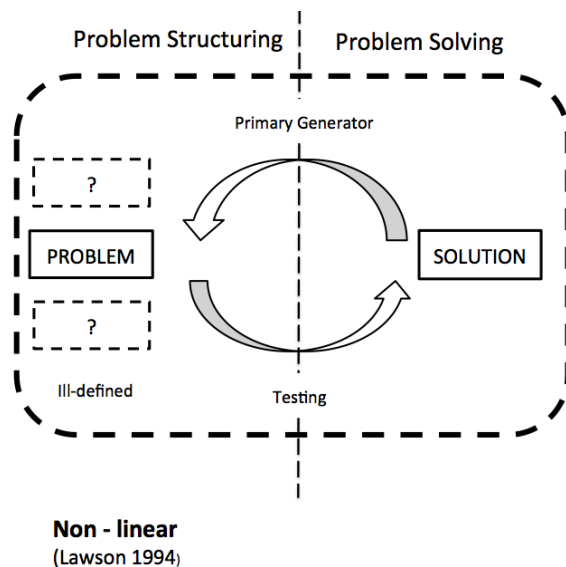


Figure 2.13 Non-linear problem solving (source: by author based on Lawson (1994))

A project that is well defined, following a linear design process (Pugh 1990; Cross 2006) is routine (Gero 1996) and results in a stereotyped design. When a project is less well defined and requires some problem structuring, but remains within the space of possible designs (Gero 1996), the solution is innovative and relies on proto solutions (Lawson 1994) or prototypes (Gero 1996). In more extreme situations where the problem is ill defined and the

solution is unknown, a creative process is needed (Cross 2006). Designers are trained heuristically in these situations to evolve processes to solve problems that have not yet been encountered (Lawson 2006). The resulting solutions are archetypes (Gero 1996), which are the first and usually unique examples of their type, and they can lead to the creation of prototypes. Figure 2.14 shows three conditions of routine, innovative and creative design problems as states of space, with solutions either in a tightly defined space, inside the space of possible designs or outside in the space of creative designs.

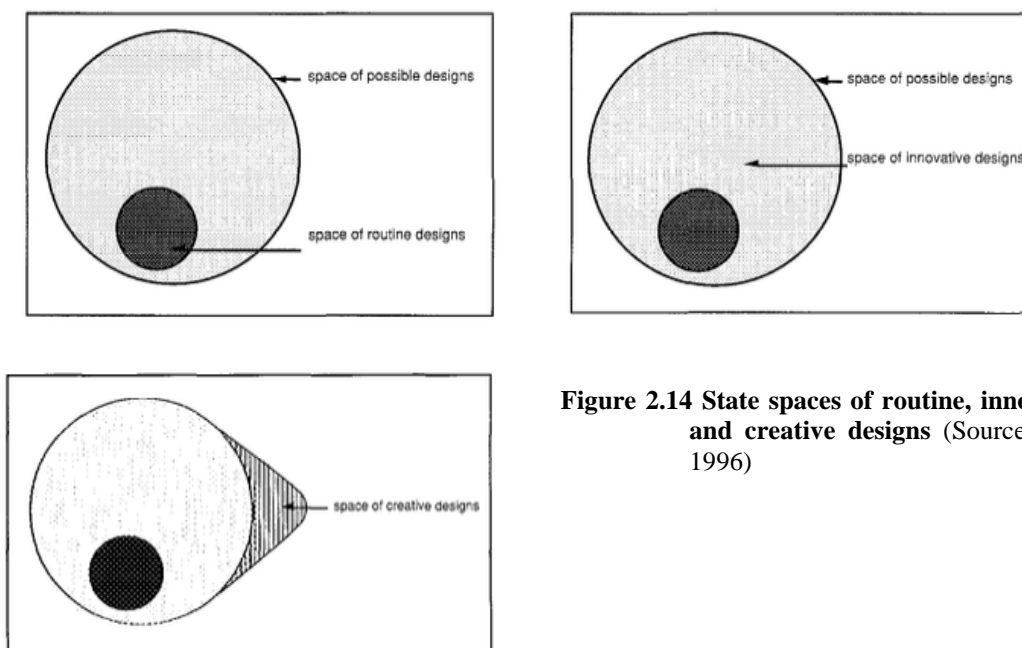


Figure 2.14 State spaces of routine, innovative and creative designs (Source: Gero 1996)

2.6 NOVELTY OF THE RESEARCH

2.6.1 AN UPDATED MODEL FOR CONSTRUCTION

Given a history of progressive but gradual change of construction through industrialisation in the last 250 years, most agree that construction is continuing to adapt to its cultural environment. The emerging perspective of digital technologies brings both new tools and added complexity to the task of efficiency in construction (Bachman 2004). These

technologies have not become prevalent, possibly as a result of low investment in construction or because of the diversity and adaptive nature of the building industry and its sub-industries (Fernández-Solís 2008). Building is also a highly contingent activity (Brand 1995; Schneider & Till 2007) and the existing models from manufacturing therefore need to be updated. By taking some elements from industrial design and its product prototyping processes (Ulrich & Eppinger 2008), this research aims to show how construction could be improved through more rationalised but responsive design approaches.

2.6.2 ISBU CONTAINERISED CONSTRUCTION

The construction industry needs well-performing products that are refined through a production process but also meet the contingent needs of buildings. Due to their successful production record in shipping (Levinson 2006) and apparent success in architectural and environmental design (Kotnik 2008), ISBUs appear to be a possible solution to some key problems in the construction industry. Their modular, standardised configuration and open product architecture (Ulrich 2003) make them suitable for modular construction with off-site manufacture of finished cellular spaces. However, while containerised construction is extensively documented on the Internet and the popular press, the application and performance of ISBUs is relatively unproven due to the lack of peer-review academic publications, which this research in part, seeks to address.

2.6.3 PLACING OFF-SITE CONSTRUCTION IN CONTEXT WITH SUPPLIER-DRIVEN PROJECTS

Previous policies have assumed that off-site, being innovative, would be a significant agent for 'step-change'. It is recognised that construction involving pre-designs and established off-site methods are part of the solution to current inefficiencies in construction. However, the

current uptake of off-site suggests that a more balanced perspective of off-site and on-site is needed. Therefore, current definitions of standardisation and preassembly are useful but need further refinement to take into consideration on-site processes. This research defines project conditions that should be favourable for supplier-driven designs and through case studies measures the combination of off-site preassemblies and on-site work in order to refine our current knowledge of this type of supplier-driven project.

2.6.4 BUILDING DESIGN PROTOTYPING

Both product prototyping (Ulrich & Eppinger 2008) and modularisation are successful strategies for reducing complexity in construction product development. While buildings are normally developed through a project rather than a product, the more advanced methodologies found in product development could offer useful models in construction. These appear particularly well suited for routine designs where physical products are used, but construction also needs better models for ill defined creative projects. Design prototyping (Gero 1996) as a methodology with modularisation as a structuring of variants, is investigated in this research to see if building designs can be more effective in contingent situations as well as routine through these scenarios.

2.7 SUMMARY

Previous research on industrialised construction suggests current theory models need updating (Fernández-Solís 2008) and new insights are needed (Eisenhardt 1989; Dubois and Gadde 2002). By combining literature from construction and product development theory this research proposes scenarios for testing out case studies that use construction product prototyping (Ulrich & Eppinger 2008) and building design prototyping (Gero 1996). The phases of project commissioning, design and production have inter-relationships that depend

on the nature of the project scenario. The processes of construction product prototyping and building design prototyping work in different ways in different scenarios. The bottom-up supplier-led and top-down client-driven approaches are linked, it is argued, to definition of briefs, design strategies and approaches to disciplinary working, and the type of production. These models are to be tested out using the case study data, but before this is described, the next chapter sets out research methods.

3 RESEARCH METHODS

3.1 CONTEXT

Given that this work is a combination of academic and practice-based research, it uses case studies to test and develop theories on product development, prototyping, and building production. This chapter summarises these methods used in this research starting with an overarching epistemological perspective and ontological approach, followed by a more detailed research design. The chapter describes methods of data collection, analysis techniques and development of theory. The research design is driven by the nature of the stated research problems in investigating a modular product and refining prototyping theory. It therefore has internal validity by maintaining a continuity between the defined research problem and the research strategy (Bryman & Bell 2007).

3.2 RESEARCH MODE AND SCOPE

The research is exploratory and concerns real-life situations which is why a case study method has been selected. The boundaries between phenomenon and context are not very clear which also suits a case study approach (Yin 2008). While the case study research is generally low level (Knox 2004), the studies are more than a rich description of data; the research attempts to match practice with theory (Dubois and Gadde 2002) and builds on these theories (Eisenhardt 1989).

Although the studies have been focussed on a sequence of projects by the sponsor, the research has external validity (Bryman & Bell 2007) through its consistency in approach to research methods.

3.2.1 RESEARCHER'S ROLE

The author has worked on some of the projects included in these studies, and from an early point in the research a conscious attempt was made to take a detached role for the data collection and interpretation. The researcher therefore was not a participant covertly observing work practices and there was no attempt to try and understand deep cultural issues within a work group for example (Dawson 2009). When research was taking place it was overt and concerned with data collection from documents and team interviews (Grauerholz, & Donley 2012).

While this data could never be 'value-free', particularly for interviews, the researcher's prior knowledge has not been completely undesirable, and when properly identified has helped to direct discussions in the semi-structured data gathering processes. Given that a clear distinction is being made between the author's own knowledge and interpretations coming directly from the data (Fellows & Liu 2003) the research process could be reliably replicated by another researcher (Bryman & Bell 2007) with similar knowledge of building design and construction

3.2.2 RESEARCH PHILOSOPHY

The epistemological position in this research is as a realist (Saunders et al 2012) rather than as an interpretivist, with the assumption that the work is dealing with accepted knowledge within a given field (Bryman & Bell 2007). Taking a view that reality can be understood if the appropriate methods are applied to a problem, a realist perspective ascertains knowledge of a reality that already exists. However, this is not a straightforward scientific generation of positivistic hypotheses, although it shares some of the perspectives of positivism by using discrete analytical strategies and is ontologically objective.

The research shifts from an empirical realism in the early stages to a critical realism in the later stages in order to address the complexity of phenomena in construction that are poorly understood. Critical realism acknowledges that structures are at work in generating events and discourses (Bryman 2008) and at that point in the research, the ontological perspective becomes constructive.

Issues of design are complex and the solutions offered through the research are not just functionalist. Constructionism (or constructivism) for example challenges the position that working methods are a pre-given, but are in fact being continually revised. However, in the first stages, the research maintains an objective position in order to weigh up the technical performance of a modular product and to describe its process as a building prototype. In the later stages, this research considers the design process through different agents, but the technical facts remain the same.

Assuming an elective affinity (Knox 2004) between philosophy and method, this research moves from an empirical realist position with a positivistic approach to experimentation through to a critical realist position with a constructivist approach on how design solutions are developed and adopted. Since methods should not dictate philosophy (Knox 2004), these trends are not rigorously differentiated, but called upon as the research develops.

3.2.3 RESEARCH APPROACH AND STRATEGY

An important decision in the research strategy was whether to collect data deductively, or to do so inductively in order to either test or build theories. Deductive data collection is objective whereas an inductive approach involves taking generalisable inferences from the

data, leading to theories being formed. The latter is an approach that is more prevalent in social research, but both approaches can occur during different stages of the same research process (Bryman & Bell 2007).

Bryman (2008) proposes a model of deductive empirical research, which ends with an inductive phase. A hypothesis taken from literature and preliminary data is scrutinized in the normal way to see if the main findings confirm or reject that initial hypothesis. Depending on the outcome of those research findings, the theory is revised through an inductive process, a process that has broadly been followed in this research.

3.3 RESEARCH METHODS

The research approach is also multi-methodological in respond to the empirical/critical realist position. A combination of quantitative and qualitative methods have been chosen due to the complexity of the research variables (Knox 2004), with the interpretation of the data crossing several cases and fields of inquiry (Cresswell 2003).

3.4 DATA COLLECTION

The following sections look at the methods employed to extract data. Case study research accepts that many variables will be present, and multiple sources of data (Yin 2003). Case study research may use theoretical development, and this becomes a vehicle for generalisation, maintaining a chain of evidence from conclusions back to initial research questions.

3.4.1 DOCUMENT ANALYSIS

Background documents have been used because, having been written for other purposes than the subject of the research, they are generally a non-reactive source of data. Project documents can therefore be relied upon as an impartial viewpoint when collected as data for research.

Bryman & Bell (2007) identify two types of documents, following John Scott (1990): personal documents and official documents (private and 'state'). To test the quality of these documents, Bryman refers to four criteria: authenticity, credibility, representativeness and meaning; these criteria have been used to verify the documents in this research.

3.4.2 SURVEYS AND INTERVIEWS

In the first part of the research there were 18 interviews conducted for the ISBU case studies, which consisted of 12 interviews of the product development team and 6 further interviews with architects and engineers involved with related projects. The sequencing of these interviews is described in Chapter 4. For the second part of the research looking in to modular pre-designs there were 27 interviews of mostly engineering staff.

Interviewing is a successful research method when exploring personalised viewpoints (Gillham 2000). Interviews are most appropriate when small numbers of people are involved, and everyone's viewpoint is key. However, to prevent the research data being biased, the interviews have to be carefully planned.

In this case a semi-structured approach is being used to reveal meaningful information in context (Fellows & Liu 2003). The position of the researcher in the process becomes more critical than in techniques using more formal questioning. As has been already discussed, during the interview process the researcher has attempted to objectify his own developing knowledge and awareness of the subject so as not to unduly influence the questions and responses in the interview process (Kvale 1996). Nevertheless, the interviewer must have a flexible viewpoint, and be aware of changing of meaning that will develop during the interview process. Interview research inevitably follows a more constructivist approach than positivist (Warren 2002). This means that the process of data collection as well as the data itself needs to be recorded and analysed. This process can then be clarified by ‘thematizing’ the research into developing areas (Bryman & Bell 2007) as will be explored later.

When planning interviews, the research position and the main developing themes should be established before preparation of a series of open questions to be introduced during the structured conversation. Multiple stages of interviews are therefore used to establish the right balance of questions.

As an alternative position on interview research, Gillham (2000) sees the structured/unstructured dimension of interviewing to be false. In his opinion, expert interviewers always have a structure, which they use flexibly according to what emerges. The most structured forms of interview are those where the interviewer knows what he or she wants to find out. This is an important assumption from Gillham, in that pre-knowledge of the subject being interviewed is the most appropriate approach to interview research, although Gillham does also describe unstructured research, which includes listening to conversations and using natural conversation to ask research questions, using mostly open-ended questions

(Gillham 2005). The research in this thesis charts a course between structured and unstructured research, using prior knowledge to the benefit of the research.

3.5 DATA ANALYSIS

3.5.1 MEASUREMENT OF TECHNICAL DATA

Measurable data such as physical properties, material quantities, and time frames have been used to quantify performance and to build on the data interpreted through documents and interviews (Fellows & Liu 2003).

3.5.2 CONTENT ANALYSIS OF DOCUMENTATION AND INTERVIEW TRANSCRIPTS

Content analysis is the most prevalent approach to qualitative analysis of documentation (Bryman 2008). Its aim is to search out underlying themes and content existing in source data. Techniques such as N-vivo coding which is used to create node routes, tree nodes and free nodes, can be used to categorise sections of identified text to then carry out content analysis (Bryman 2008).

Content analysis is very transparent, because it is replicable, and even allows some longitudinal analysis. It is unobtrusive, and has no reactive effect on data and is highly flexible. However it is dependent on quality of data and documents, and it is impossible to avoid some interpretation by coders, particularly for latent (hidden) rather than manifest content. It doesn't answer "why" questions and it is commonly accused of being atheoretical. Therefore it is important to follow methods, and to make sure categories are discrete and mutually exclusive. An approach to thematic analysis and coding therefore is outlined next.

3.5.3 THEMATIC ANALYSIS USING CODING

Thematic analysis is a technique widely used for ordering data, but it is not attributed to any particular research approach (Bryman 2008). The method uses an analysis framework based on a matrix for sorting data into core themes and sub-themes. In coding there are two basic stages: categorisation of material and grouping of data under different categories by assignment of data tags (Bryman 2008).

The following stages for coding have been used in this research:

- Categorisation through Open Coding
- Re-arrangement of data using Axial Coding
- Selective Coding to formulate propositions for further research

Transcripts are broken down into short sentences and phrases to define categories. The research is looking for repetitions of words and reoccurring topics as well as metaphors that are similar ways of presenting the same points. The phrases are then rearranged around core themes or topics. The research then reflects on data that might be missing, and uses existing models for exploring themes.

3.6 SUMMARY OF THE RESEARCH DESIGN

While the philosophical position for the research has tendencies towards critical realist in the later stages it is mainly empirical realist, using a deductive approach to test and an inductive phase to refine existing theories, with a case study strategy of mixed methods research combining case study data and interviews in a cross-sectional time frame. The data from the

case studies is being studied using quantitative numerical analysis and qualitative thematic analysis to draw out findings to test against general theories from literature. The numerical analysis comes from the measurement of engineering performance in terms of ISBU standard dimensions, structural, fire and acoustics performance and this is compared with the relevant UK and European standards. Quantities of materials for different construction methods are also measured in order to understand in detail the different levels of preassembly used as defined in literature. The project documentation and interviews provide data for qualitative analysis in order to identify product development processes, production and procurement strategies.

4 ISBU MODULAR CONSTRUCTION DATA (WPS 1-3)

4.1 INTRODUCTION

For the two main case studies, the sources of data for analysis were team interviews and project documentation. The interviews were carried out in multiple stages to direct and support central findings in the case studies. These findings have been compared with data from other projects involving product development at Buro Happold, as well as similar case studies involving multi-storey building construction that is non-modular.

4.2 SCOPE OF RESEARCH FOR ISBU MODULAR PRODUCT DEVELOPMENT (WP1)

In 2002 the consortium was formed between CIMC, Buro Happold and G&H contractors to develop an ISBU that could be manufactured in large volumes for the building construction market. The product development process occurred over an extended period of time. Design team interviews with the product design team were believed to be the most effective way of capturing previous development decisions, and also provided an opportunity to explore appropriate themes within the research and were therefore conducted as open conversations.

4.2.1 OPEN INTERVIEWS WITH THE PRODUCT DESIGN TEAM

This first data came from 13 open interviews conducted with the design team members, the product manufacturer and a client. Those interviewed were:

- Engineering Design team: partner, associate directors, senior technician, associates and engineers (A to G)
- Architect (H)
- Manufacturer: product developer, funder, manager/promoter (J, K, L, M)
- Client (N)

As open interviews, the conversations were semi-structured conversations. All the interviews started with the same first question:

“What does Verbus (the product) mean to you?”

This was followed by further questions along the lines of:

“What do you think about the building system?”

“What are the main issues with modular buildings?”

“How could the product be developed further?”

4.2.2 DATA ANALYSIS OF FIRST INTERVIEWS

The analysis was broken down into three phases: 1) preliminary sorting of data and categorisation using open coding, 2) axial coding along central themes and 3) selective coding to formulate further propositions for research.

4.2.3 PRELIMINARY SORTING OF INTERVIEW DATA AND OPEN CODING

When the data was initially analysed, the following words were observed to be the most commonly repeated: ‘Product’ (38), ‘Module/modular’ (30), ‘Standard/bespoke’ (12), ‘System’ (13), and ‘Cost’ (10).

Mind mapping software (Mind-Manager Pro) was used to sort the data to draw out topic headings. Initial topics to emerge were: commercial issues, programme, supply chain, product characteristics, design, technology and construction and product perception.

After this initial mapping the data was open coded into core themes based on PESTEL (Political, Economic, Social, Technical, Environmental and Legislative) issues. Key phrases

(145 No.) from the transcripts were measured for their content under those themes and the following categorised topics.

1. Economic- market, financial, quality, programme and commercial
2. Social – knowledge, information and perception.
3. Technical - design/research & development, adaptability, standardisation, CAD/BIM & parametrics, manufacturing, transportation, construction site.
4. Environmental – waste and carbon footprint.
5. Legislative – contracts and planning.

It was found that a significant part of the data (59%) was linked to technical or economic issues. All themes were analysed further but technical and economic issues were taken furthest into the next stage of research.

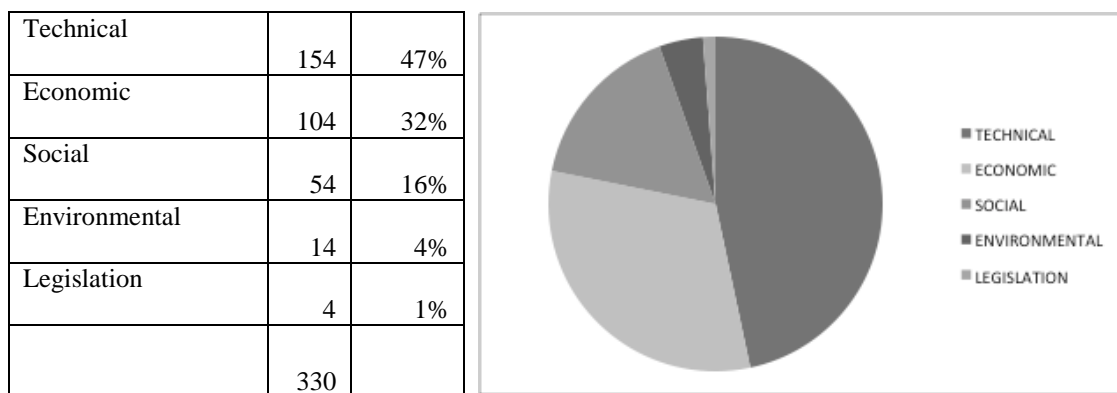
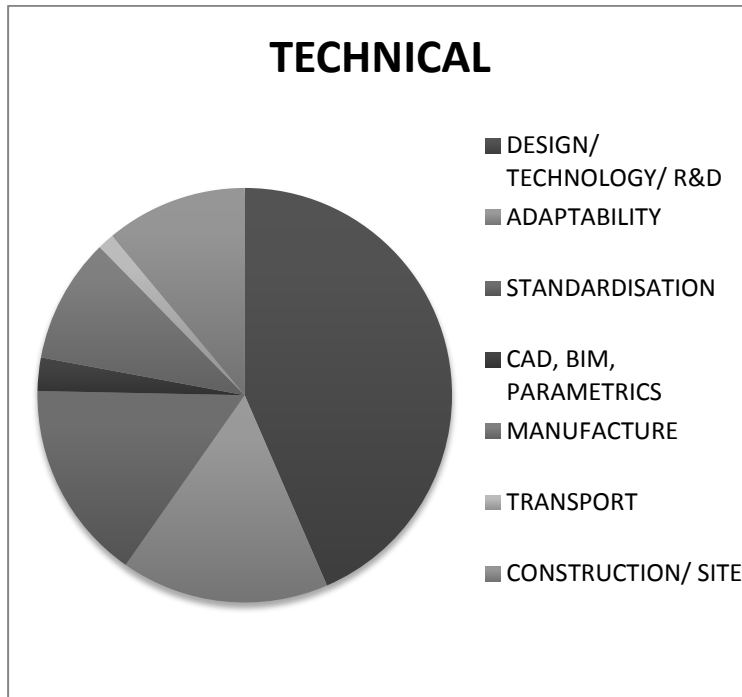


Figure 4.5 Distribution of open coded data using PESTEL core issues

4.2.3.1 Axial coding of interview data for technical and economic issues

Following this open coding, data linked to the core themes of technical and economic issues were sorted into categories. The data was also further sorted into sub-categories of ‘Product’ i.e. what was done, and ‘Process’ i.e. how it was done. Data is presented in Figures 4.6 to 4.7 as a distribution of categories under the core technical issue.



TECHNICAL		Product	Process
Design, technology and research	67	41	26
Adaptability	25	15	10
Standardisation	24	13	11
CAD, BIM, Parametrics	4	2	2
Manufacture	15	7	8
Transport	2	2	0
Construction/ Site	17	8	9
TOTAL	154	88	66

Figure 4.6 Distribution of categories under technical issues

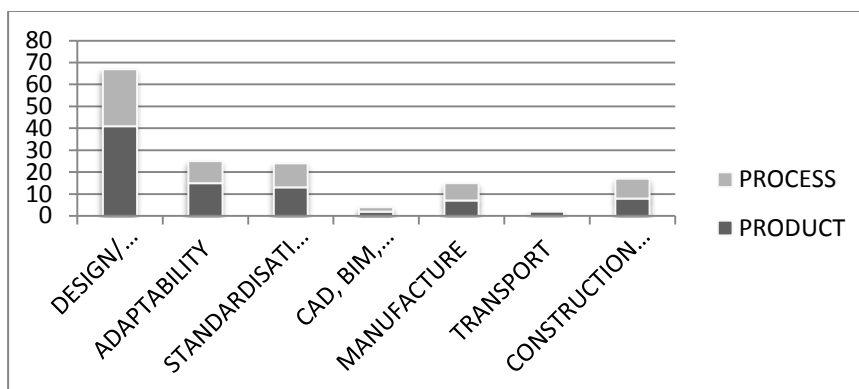


Figure 4.7 Distribution of 'product' and 'process' for technical issues

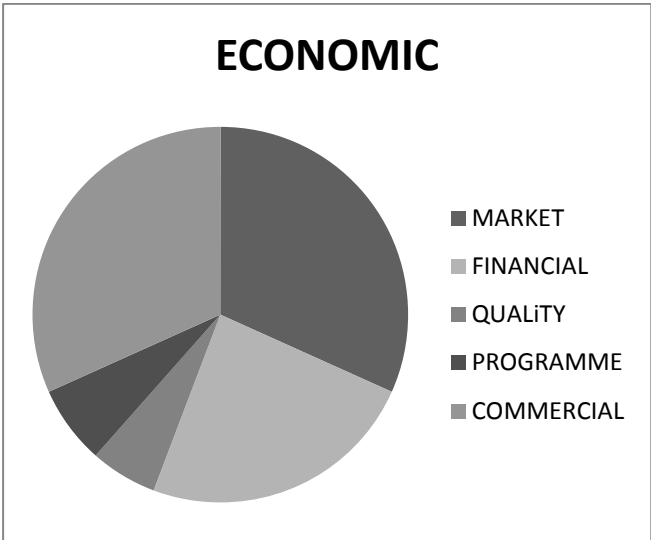
The most commonly occurring categories were 'design, technology and research', followed by 'adaptability' and 'standardisation'. There was a slightly greater focus on the product

technology, but product and process were overall found to be of approximately equal importance for technical issues.

Adaptability and issues linked to adaptability were raised many times in the interviews (25 times) and during the research it was found useful to define what this category meant in greater detail. Adaptability and similar expressions had been used in the interviews to describe:

- How well the base product could be adapted to suit national and international markets
- Adapting the product to different sites and conditions
- Flexibility of the design for temporary or permanent application
- Making it suitable for different applications
- Allowing the product to be extendable, having removable side walls, allowing other structures or cladding to be added
- Robustness of the product, its design life, and ease of refit.
- Its ability for re-use, being self-contained with autonomy from other structures.

Similar axial coding analyses were carried out for economic issues as shown in Figures 4.8 to 4.9. They identify market and commercial as well as financial to be most dominant categories, with product being very pronounced under the category of market.



ECONOMIC		PRODUCT	PROCESS
Market	33	24	9

Financial	25	12	13
Quality	6	4	2
Programme	7	5	2
Commercial	33	15	18
TOTAL	104	60	44

Figure 4.8 Distribution of categories under economic issues

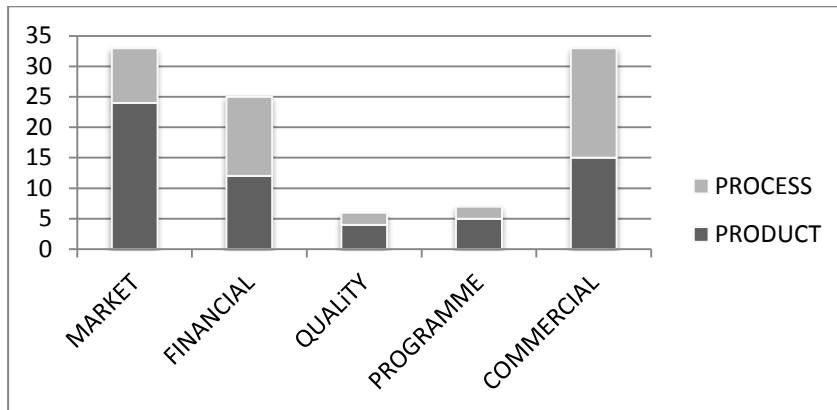


Figure 4.9 Distribution of 'product' and 'process' for economic issues

Based on these findings, it was decided to take forward product market application and process of commercial realisation as categories for further analysis and selective coding.

4.2.3.2 Selective Coding of the first interview data

Interviews and documentation were therefore analysed for technical research, product market application, and its commercial realisation. On the topic of technical research there was significant optimism for the product itself. Although it was,

“a less standard form of construction research” (Engineer A1),

it had

“*obvious sensible applications*”(Engineer A1).

The modular building component as a concept was considered to be

“...really good, has global deployment, can be used with any cladding ... and is much less complex, and more robust than similar products” (Architect H1).

Other characteristics mentioned were ease of transportation through existing infrastructure and coming from China has the potential for

“a major production line, to produce enormous volumes...” (Engineer F1),

making the product

“attractive and competitive to builders” (Engineer H1).

The product developers, who came from a UK contracting background, had negative opinions on existing modular construction systems.

“..the concept/perception of modular construction in the industry is that it is cheap, temporary and lightweight ” (Manufacturer J1).

Therefore, they were deliberately trying to establish a product that was unlike other modular systems in its robust construction.

“With (the product) there has been a deliberate policy of over-design. It needs to feel like a building” (Manufacturer J1).

Their contractor experience had led them to conclude that construction products need to be able to cope with the contingent nature of building.

The steel modules were therefore quite heavy compared to other products and there had been suggestions by the design team that the product could be refined and adaptable.

“(We) need to take steel out, take panels out and provide more integration of other modular elements, M&E.... ”(Architect H1).

However, the central goal of the manufacturer was to keep it very basic.

“With (the product) we are not talking about the flexibility of a framework. Being a cellular structure, we can cut openings, but that’s all” (Manufacturer J1).

“Many say that ‘the system is highly under-developed...there is a lot to do’. But...you need to look at what is the main benefit to the client... (only) a fully furnished bedroom, with window and rails is worth pursuing.” (Manufacturer M1).

The manufacturer wanted to maintain a very simple core product, and the interview data evidenced perceived needs in the design team for market adaptability against an aim by the manufacturer to product a basic product.

The design team identified that that the market placement was still undecided and could go in one of either two directions.

“..how it fits into the market, I know we’ve talked about this a few times, there is a route that you go to where you go to a contractor and say this is a system that you can use” (Engineer F1).

“Another way.., is that you try to find buy-in from the design community, and we show that it is a versatile product and get them to specify it” (Engineer F1).

However, some in the design team also felt that the flexibility argument was problematic.

“..the times that I was involved, (I) was trying to force it into a scheme that had already been designed for something else.. or you were trying to force in onto an architect, and trying to get them to change their design, which didn’t quite fit in” (Designer F1).

“We now seem to be adopting a new system for each project, (it is) not standardised...” (Engineer D1)

As a result there was a desire to make the product as standardised as possible for modular construction.

“This is why standardisation is so important: you have a design system which means you can react quickly, design faster and save money (Engineer D1)”

“..(we need to) look at whole building. (We) should go through everything (that is) different. Modular needs repetition” (Engineer E1).

“The concept is about mass production and high volume. It has got to be standardised. We have got to do more of the standard product” (Manufacturer K1).

For the process of commercial realisation, the issue of value started to become more important.

“...it’s justifiable to do something like this only if it results in an improvement to quality, and getting a better product otherwise, if you get the same.. builder to build it in the usual way, they get more profit from it” (Engineer F1).

“Initially we focused on price, back in 2007.... We lost a lot of money. It was difficult in those early days but we wouldn’t do the same this again. Our approach now is to focus much more in giving value to the end client/developer. We are trying to work with the main contractor to take out as much cost in the project” (Manufacturer L1).

The main focus on value came through the way the product was applied on site and in the later projects this was how savings began to be realised.

“A standard product has large benefits to contractors... As they have progressed (with previous hotel buildings) far less supervision has been needed; there have been less defects” (Manufacturer K1).

“Heathrow proved it could be done in 11 months. (The contractor) was asked how long it would take normally – 18 months. Speed is of the essence for hotels” (Manufacturer J1).

“I’d like to come back to Commercial Value. I think that Commercial value for Verbus is selling the value of the efficiency that the Verbus process can bring to the construction industry. The contractor has less people, there is less site time, the client opens early and there are better terms of investment (Manufacturer M1).

4.2.4 RESEARCH PROPOSITIONS

Using this data on product, market and commercial realisation led to the following research propositions, which shaped the remainder of the research.

The product had positive aspects and could be refined but this needed to happen without losing its robust nature. The main focus seemed to be on standardisation of the basic room module with good interfaces to cladding. The research should therefore look at how well these goals were being realised.

There appear to be two routes to marketing the product, either via the contractor or to the ‘design community’ and a central question to procurement is whether the product can be

supplier-driven (with the contractor) or client-led (with the designer). In considering these two routes, the research should consider how this affects the product and where is the most appropriate market.

Based on these propositions, the next stages of the research looked at the product development and its technical performance (WP 2), and it looked at how the market, whether supplier-led or client driven (WP 3), would lead to different production and procurement strategies.

The interviews also detected an anticipation that design practice could or would change as a result of modularisation.

“From an engineer’s perspective, there will be change. Every building will be less bespoke; we will not be ‘reinventing the wheel. For architects I think it will be different. They might not find it as appealing, (with) limitations (on) ..their creativity. Maybe in (the future it will be about) generating forms with modular components” (Engineer C1).

The possibility of better product outcomes could lead to greater design standardisation, and this is taken further in the second part of this thesis with the rail station case studies that followed this research (WP 4).

4.3 ISBU CONSTRUCTION PRODUCT PROTOTYPING (WP 2A)

In order to understand the full process of technical product development for the ISBUs, 54 documents were chosen from the project file directories as being key sources of information. These included: project briefs, building programmes, employers’ requirements, design manuals, certification manuals, plan layouts, structural analysis calculations, acoustic reports, fire analyses, façade detailing. prototype specifications, test reports, unit fabrication drawings, patents, warranties, and method statements. A list of the key documents and their authenticity, credibility, representativeness as well as meaning is given in Table 4.1.

Document Type	No.	Authenticity	Credibility	Representativeness	Meaning
Project briefs	3	High	High	Medium	Medium
Building programmes	3	High	Medium	Medium	Low
Marketing Reports	5	High	Medium	Low	Low
Publicity articles & news	8	High	High	Low	Medium
Contracts, employers' requirements	3	High	High	Medium	Medium
Design & certification manuals	10	High	Medium	Medium	High
Plan layouts	n/a (100+)	High	High	Medium	Medium
Engineering analysis & calculations	2	High	High	High	High
Test reports	6	High	High	High	High
Meetings & workshop minutes	13	High	High	Medium	Medium
Unit fabrication drawings, patents & warranties	n/a	High	High	High	High
Method statements	1	High	High	High	Medium
Total	54				

Table 4.1 List of document types to test authenticity, credibility, representativeness and meaning

4.3.1 PRODUCT DEVELOPMENT OF THE ISBU HOUSING PRODUCT

The consortium was establishing a market for the new container, an early prototype for the ISBU was developed in 2002 for a domestic house product. Three 20 ft. (6.1 m) container units were manufactured in China and delivered to the UK. See Figure 4.10.



Figure 4.10 Shipping and unloading of purpose-made containers from China for the prototype house (source: Verbus)

The house layout was based on an arrangement of standard length containers with the units being 1.5 times the standard 8ft (2.4 m) width at 3.6 m wide.

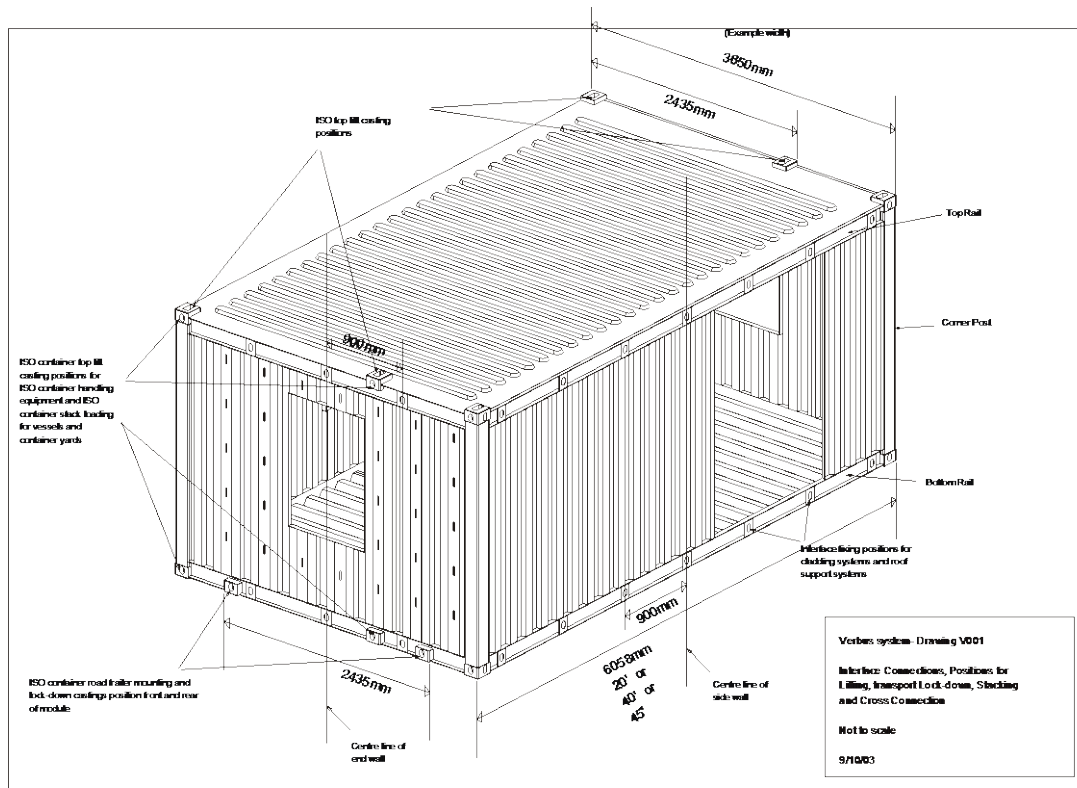


Figure 4.11 20 ft. (6.1m) x 12ft (3.6m) ISBU container for domestic house production (source: Verbus)

Figure 4.11 is a drawing of a container produced for the house prototype. The unit is made up of a frame of steel box sections and channel sections in 6mm plate stiffened by 1.6 mm thick corrugated steel walls. As well as the normal eight cast steel corner lifting points, two additional castings are shown added top and bottom so that two larger width containers could be stacked on top of three standard 8ft wide containers. In the final production version of the drawing four cast lifting points were added to the top and bottom of the ISBU so that the unit could be lifted and loaded in symmetrical configuration at ports and on road trailers as can be seen in Figure 4.10. The empty containers, with their low weight were loaded on the highest

tier of the container ship, a position used for transporting empty containers, which benefited from lower shipping rates than normal dry bulk containers.

The units still had some openings in the sides, roof and bases, which were sealed for connections between rooms and stairs and these were sealed with temporary welded plates during shipping. The units were stacked and assembled as shown in Figure 4.12 at a site in the UK near Broxbourne. Since the units had been shipped unfinished, and simply lined in plywood, they were fitted-out on site and clad in cavity wall brickwork.



Figure 4.12 Assembly and completion of prototype house at Broxbourne, UK (source: Verbus)

The intention for future product runs was to complete most of this in the factory, including part of an insulated masonry cavity wall attached to the side of the unit complete with window and ledge as shown in Figure 4.13. The challenges of developing the skills and supply chain networks for this in China were considerable, and happened very slowly through later projects as will be shown through the stages of product development.



Figure 4.13 Proposed container unit with pre-installed masonry cavity wall (source: Verbus)

Due to a lack of interest in the market for a house product, the project stalled with the first prototype. However, the product developers gained experiences on the manufacturing process with CIMC, shipping and detailing of the unit. In later multi-storey buildings a cavity wall was added to the units, supported on brick shelves and stainless steel ties face fixed to plates welded across the corrugations on the 1.6 mm steel sidewall panels. These walls were added on site; the development team had planned for walls to be added in the factory. See Figure 4.14.

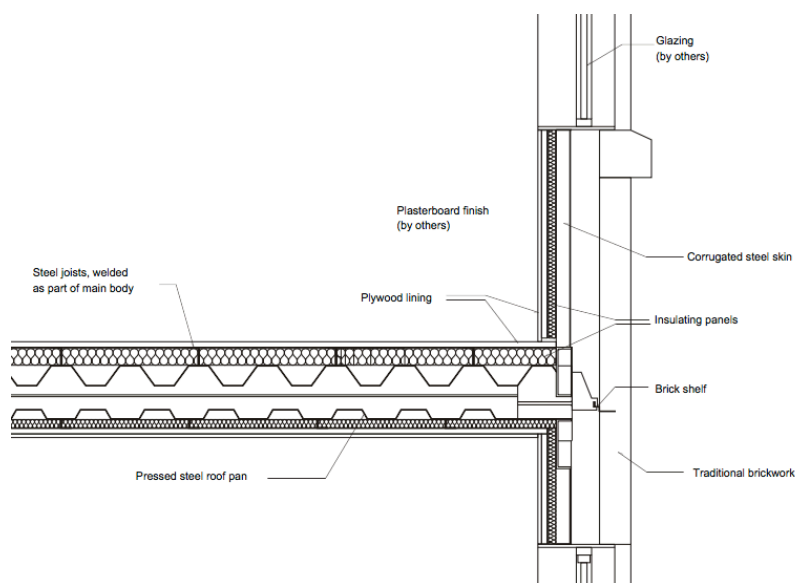


Figure 4.14 Floor/ceiling and external cladding section build-up to module

4.3.2 ISBU PRODUCT PROTOTYPE FOR MULTI-STOREY ACCOMMODATION BUILDINGS

Alongside this domestic market model, proposals were being established for a multi-storey accommodation building. Some 20ft long prototype bedroom units were designed and then manufactured by CIMC with a lined plywood interior.

For multi-storey construction a vertical riser as already shown, needed to be incorporated into the module and Figure 4.4 has previously shown such an arrangement. The stud walls had a 75mm wide insulated cavity and the roof and floor had a 100 mm insulated cavity covered by an 18 mm plywood lining. The depth of insulation at this stage was governed by judgments on the likely performance of the units for air-borne sound and impact noise absorption. The performance of the building layers against acoustic transmission was tested in the first building installation that followed in 2005.

Without any orders for housing, the development team started to look at multi-storey construction. A completed student housing in London called the Queen Mary III block, the Lillie road social housing project and Merton Abbey Mills housing development, designed by architects Feilden Clegg Bradley, were used as the product scenarios for the new ISBU product. At this stage, the product development team members were still establishing an appropriate configuration and size of units.

The completed student-housing block that had used a conventional reinforced concrete construction, was seen as useful test scenarios for the alternative volumetric module. Module layouts were over-laid onto existing plans to see how much of the project could be standardised. Given a large number of student bedrooms, this housing block was reconfigured to suit the container module. The student building curved in plan and also consisted of non-standard areas such as kitchens and living rooms which had to be accommodated into the volumetric model which led to some inefficiencies. It was noted, for example that the curved plan led to a loss in floor area, due to the cranking of the modules as shown in Figure 4.15.

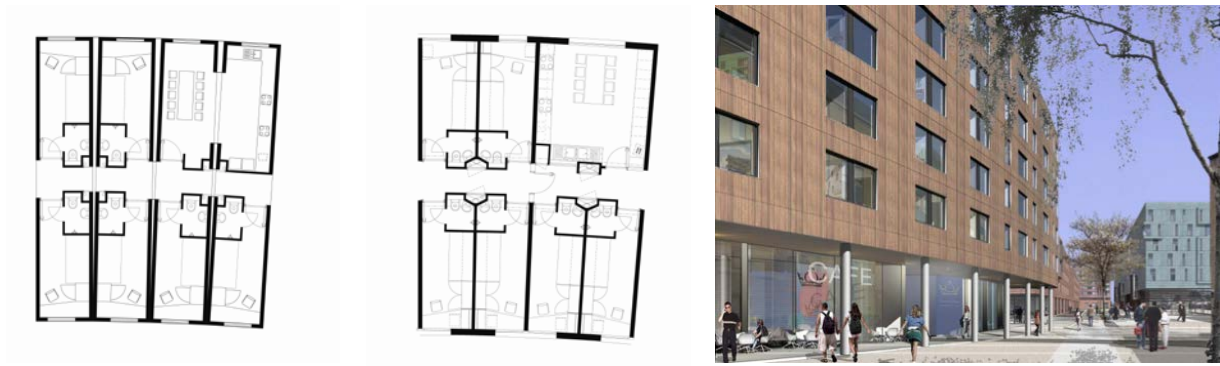


Figure 4.15 Conventional layout and volumetric module proposals on a curved plan for Queen Mary College student housing

Initially a 2.4 m (8ft) wide module was proposed for the student housing, but in the social housing scheme, this was felt to be unviable as a room width dimension and a wider module was proposed. The 3.6 m (1.5 x 8ft) x 6.1 m (20ft) modules were used with a standardised layout of repeatable units around a non-standard stair and lift core as shown in Figure 4.16.



Figure 4.16 Social Housing layout of standard 3.6 m wide modules based on Lillie Road

After several attempts to commercialise these and other versions of the module for student accommodation, social housing and prisons, it became apparent that the best opportunities for commercialisation of the product would be through the longer 40ft module containing two rooms back to back across a corridor section. Although units were wider (3.6 m), the 12.2 m module would benefit from lower manufacturing and transportation costs compared to two

shorter 20ft units, and it was this 40ft+ unit, as shown in Figure 4.17, that was proposed for subsequent hotel developments,.

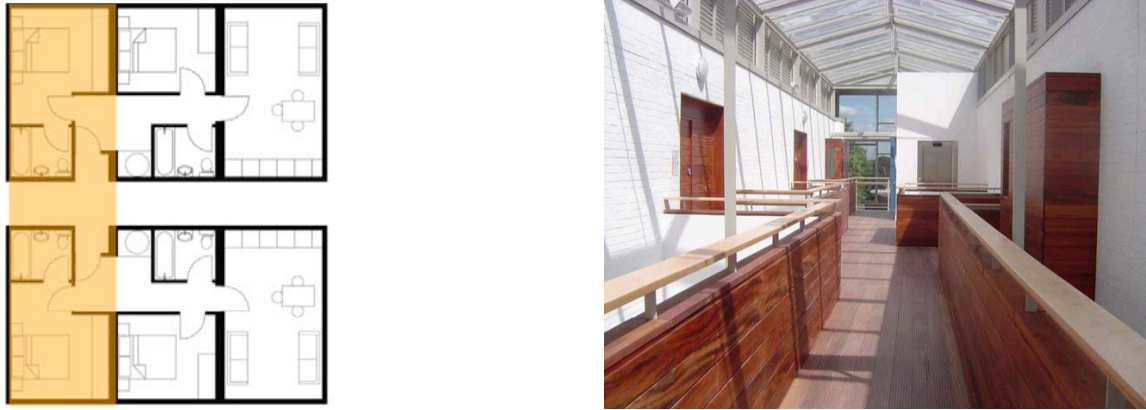


Figure 4.17 3.6 m wide x 12.2 m long bedroom and corridor units for Merton Abbey development

A similar configuration of units to this was applied to the budget hotel buildings that followed. The minimum size of hotel rooms defined in each hotel brand standard meant that the multiple bedroom units needed to vary not only in width but also in length by more than the standard 12.2 M (40ft). Typical lengths of 13 to 15 m were needed. It was established by their transportation consultant that the oversized containers could be accommodated on containerised shipping and road transport and a total overhang of up to 2.8 m would be possible without impinging on the constraints set by shipping and transport providers working to ISO standards. However, with the requirements of ISO 668 for stacking and lifting of freight container modules with standard lifting points, this meant that the corners of the oversized units would not match other containers and needed an additional eight castings on the roof and on the underside of the units to match the possible configurations of the 40 ft. dry container, crane lifting points and road trailer fixing point positions.

4.3.3 UNIT CONNECTOR PRODUCT PROTOTYPING

ISO containers benefit from a standard arrangement for connecting and disconnecting lifting equipment, connecting to road and rail transport and connections to shipping and between

stacked units in dock storage or on the container ship. These connections are self-locking devices for ease of connection and several existing products are available on the market. However, none of these products are designed for permanent building use, and the design team started to develop a more permanent connection system based on a connector that would work with the standard locking points found in a container. There was also a need to develop a means of connecting adjoining units to create a robust connection for transmitting tie forces horizontally as well as vertically between the units as will be discussed in further detail in later sections on the engineering of the unit designs.

A permanent connector exists, the German Lashing QT-TV as show in Figure 4.18, and the proposed connector was a hybrid of existing products. However, it needed to be adjusted to accommodate shimming plates, which needed a longer thread, and a top locator cone to aid unit alignment and installation. Locator cones could have been developed from existing German Lashing designs but the start-up costs of manufacturing the new permanent connector could only be justified for a large order of connectors, and this design was put on hold until there was greater demand for the product.

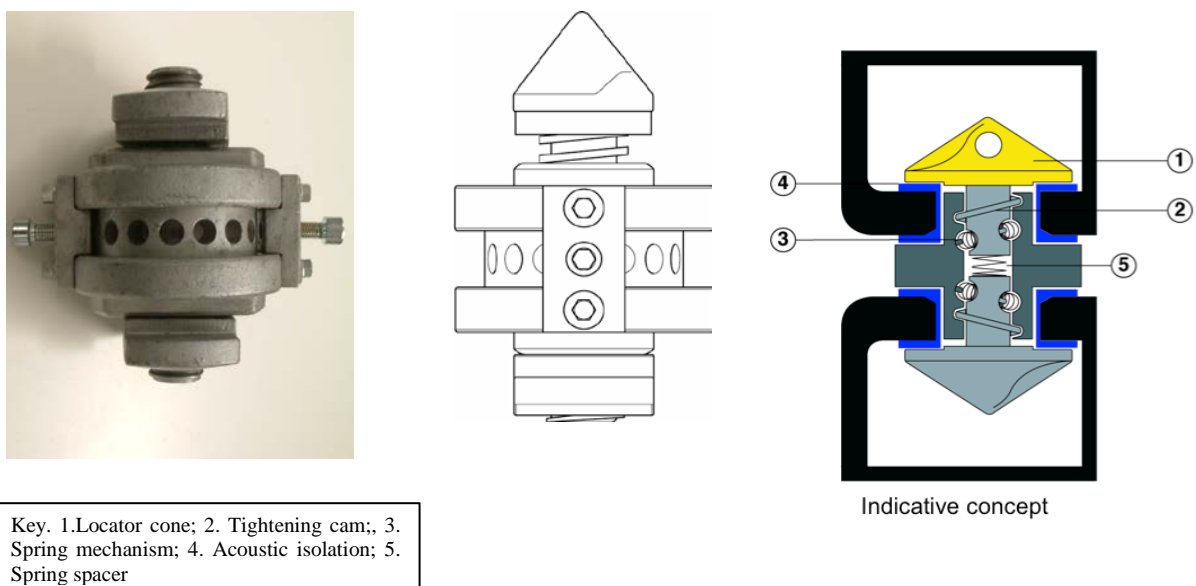


Figure 4.18 Example of German Lashing QT-TV permanent container unit connector & proposed adaptations with self-locking cones (source: Buro Happold)

Further ideas were developed for a locking and bolting device as shown in Figure 4.19. This design was also not taken forward, and as an interim measure a simpler arrangement of bolts, locating spigots and connector plates was used in the first projects as will be shown in the following sections.

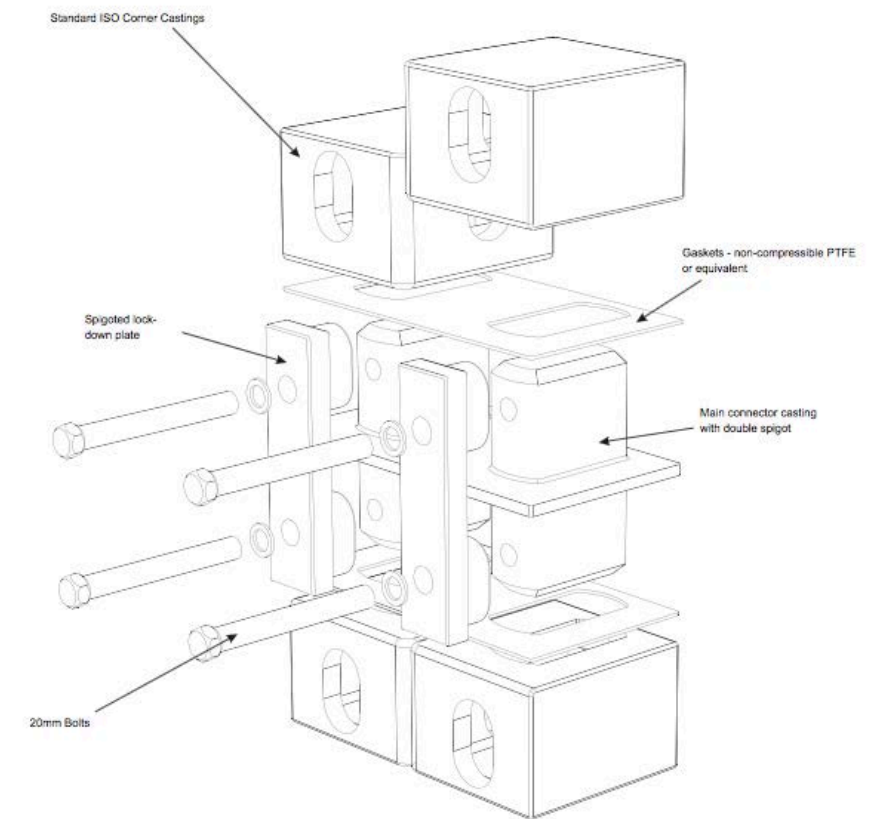


Figure 4.19 Design for an external bolted connection combined with horizontal plates

4.3.4 FURTHER PRODUCT INNOVATIONS ON PROJECTS USING THE NEW ISBU PRODUCT

A design manual was created to market the product, identifying the product characteristics and different possible configurations.

From 2004 to 2009 seven budget hotel buildings were constructed using the bedroom/corridor/bedroom configuration including a construction product prototype for a standard hotel building. As outlined in Papers 2 and 4, there was a gradual transition from a preliminary lined container shell with 1st fix M&E in 2004 to a fully fitted out bathroom in 2009.

After an initial prototype two-storey hotel installation for Travelodge in Bath, the first multi-storey building for an eight-storey hotel was assembled for Travelodge in Uxbridge, Middlesex. See Figure 4.20. The layout of this hotel on a very tight corner site was not suited to large numbers of standard 40ft+ units, but the constraints of the site adjacent to a bus station operating 24 hours a day was an incentive to maximise off-site methods, and so this became the first tall building to be constructed using the new product.



Figure 4.20 ISBU container modules being assembled at the first multi-storey container building for Travelodge, Uxbridge in 2005 (source: author).

The units stacked directly on top of each other with additional steel framing used to accommodate non-standard stair cores and open-plan building areas at the ground floor. As shown in the layout for the Uxbridge Travelodge in Figure 4.21, the units were arranged in blocks around triangular core areas.

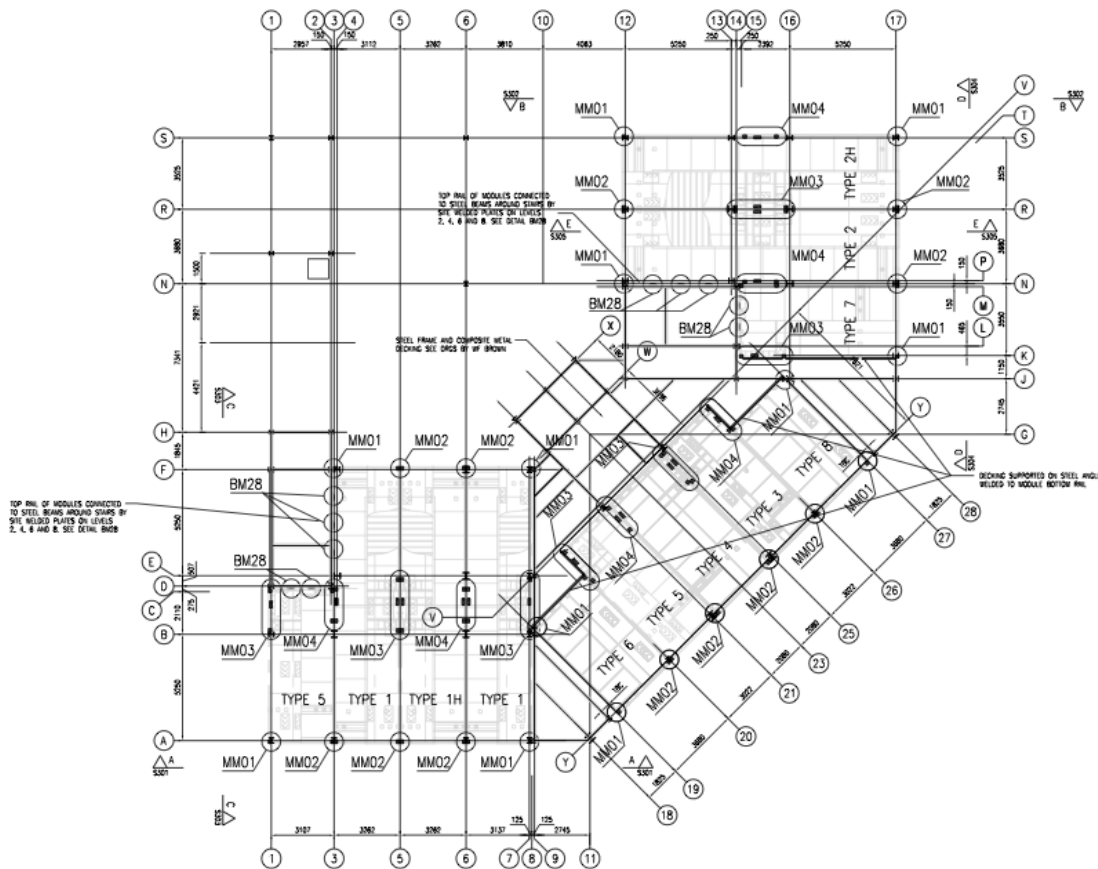


Figure 4.21 Layout plan for Travelodge hotel units at Uxbridge (source: Buro Happold)

The first two storeys were steel frame construction supporting 7 storeys of ISBU container modules, providing 181 bedrooms in 86 modular units. 60% of the units were of 40ft+ length, with shorter modules to accommodate steps in building plan layout and bays for standard structural steel staircases. In total, there were seven different module types including wider bedroom modules for disabled users.

Without a workable solution for a permanent connection using the cast steel lifting point, units were connected vertically via an additional bolt box connection fabricated in the units as show in Figure 4.22.



Figure 4.22 Standard vertical bolted connections between units with packing and link plates (source: Buro Happold)

By the third project in 2006, the shape and position of locator spigots were refined and simplified for incorporation into steel base frame as shown in Figure 4.23. While the tolerance on width and height of units was ± 4 mm, the 40 ft. (12.2 m) long units could vary in length between ± 12 mm. Taking into account possible variations in steel frame to NSSF (5th Edition), overall tolerances in the base spigot locations allowed for up to ± 25 mm tolerances using spigots of different RHS profiles with different orientations.



Figure 4.23 Spigots on base steel frame for locating and positioning containers and link plates welded between units and structural frame. (source: Buro Happold).

Containers were located via these base spigots and interconnecting spigots between units. The units were also linked to steel frames through plates welded on site as also shown in Figure 4.3.

The corner lifting points were used for onsite lifting and attachment of safety equipment such as man-safes; this avoided the need for perimeter protection during installation as show in Figure 4.24.



Figure 4.24 Lowering of units guided by site installers wearing man-safes (source: author)

In most cases a perimeter scaffold was added for installation of external cladding. See Figure 4.25. In some cases the units were delivered and craned over the external scaffold.



Figure 4.25 Lifting units at Heathrow Travelodge with perimeter scaffold being added (source: author)

Further innovations during the early projects included the design of intermediate steel frame make-up pieces where stacked units did not align with the levels of the building being

constructed in conventional steel frame. The ISBU producer determined that it would be more cost effective to install these separate make-up frames rather than change the height of units on the lower floors. Depending on the difference in floor levels, these frames varied from 400 mm to 1400 mm high. For make-up pieces less than 400 mm steel corner blocs were used. See Figure 4.26.



Figure 4.26 Steel make-up pieces to accommodate changes in storey heights between units and main building structure for Heathrow Travelodge (source: author).

The Heathrow Travelodge in 2006 and for a similar project for the Gatwick Premier Inn, the bedroom and bathroom were fitted-out in the Chinese factory with installed services, finished walls, bathroom and fixed furniture elements to the hotel brand requirements. See Figure 4.27. The Premier Inn brand standard manual, an extract of which is shown in Figure 4.28 describes minimum dimensions of rooms, position of doors, fixed and loose furniture, fittings, options for AC unit and general wiring requirements.



Figure 4.27 Bedroom unit (Gatwick Premier Inn) after installation during secondary fit out (source: author)

At Heathrow, there were issues over the quality of the installed fittings and wiring standards, which was rectified for the Premier Inn at Gatwick but required increased supervision and product control in the factory.

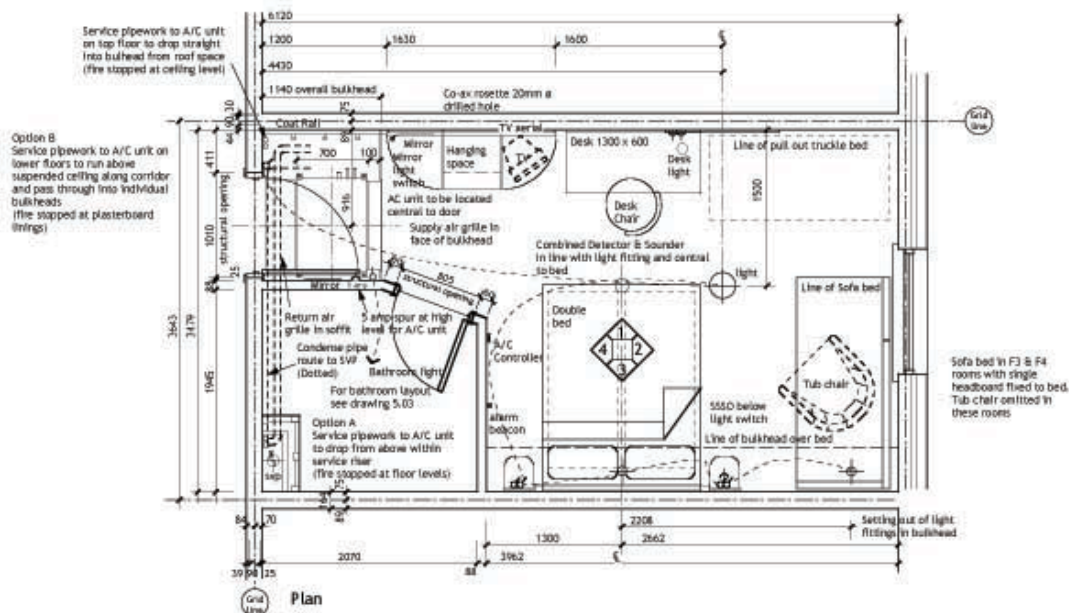


Figure 4.28 Extract from a brand standard drawing (source: Premier Inn)

The tallest structure built using the ISBU product was the Hull Premier Inn, built in 2007. See Figure 4.29. Six storeys of container units were built on a steel frame housing a hotel reception/dining area and six levels of car parking.



Figure 4.29 Premier Inn, Hull during installation of final level of units (source author)

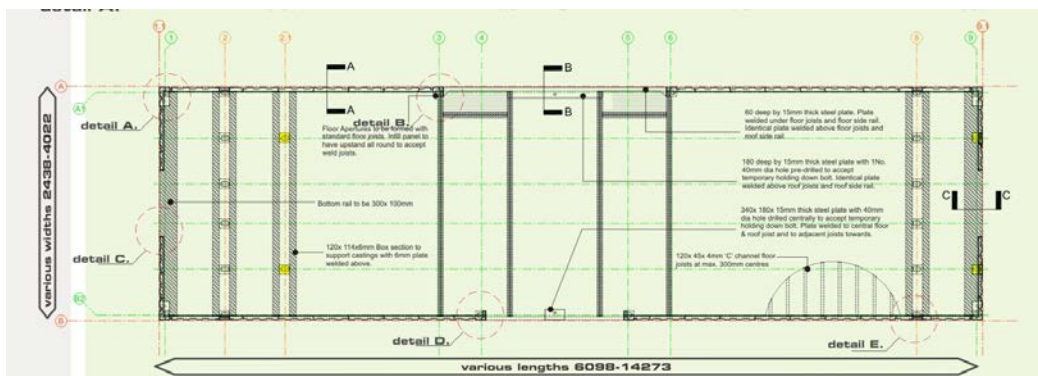
Many of the refinements of the previous projects for unit structure and fit-out, connections and locating spigots were realised on this project and the product manufacturer attempted to offer the product as a supply-only contract. However, this was not acceptable to the main contractor and Verbus took responsibility for the installation of the units. There were issues with the tolerances of the steel frame; it was significantly out of vertical alignment, and the steel erector had to make adjustments to the frame at the upper levels to bring it back into tolerance. This was only partially successful and there were problems with installing the units to tolerance with a knock-on effect to the cladding installation. The cladding had been designed to absorb some tolerances in the frame, but around the window openings there was too much out of tolerance to accommodate so the openings in the units had to be modified and re-finished. This required significant work but was possible due to the additional capacity in the structural steel box. With the modified units, the project was completed; the finished building is shown in Figure 4.30.



Figure 4.30 Premier Inn, Hull(source: Premier Inn)

4.3.5 FINAL PRODUCT DETAILS

The standard ISBU has a frame of steel box sections and channel sections in 6mm plate, stiffened by 1.6 mm corrugated steel walls, a 100mm layer of mineral wool insulation, 9 mm plywood on steel studs and up to two layers of 12.5 mm plasterboard lining as shown in the Figure 4.31. The units have a number of castings set into the roof and underside to suit the different locking positions during transport. Corner castings also provide points for locating pins during assembly as previously identified.



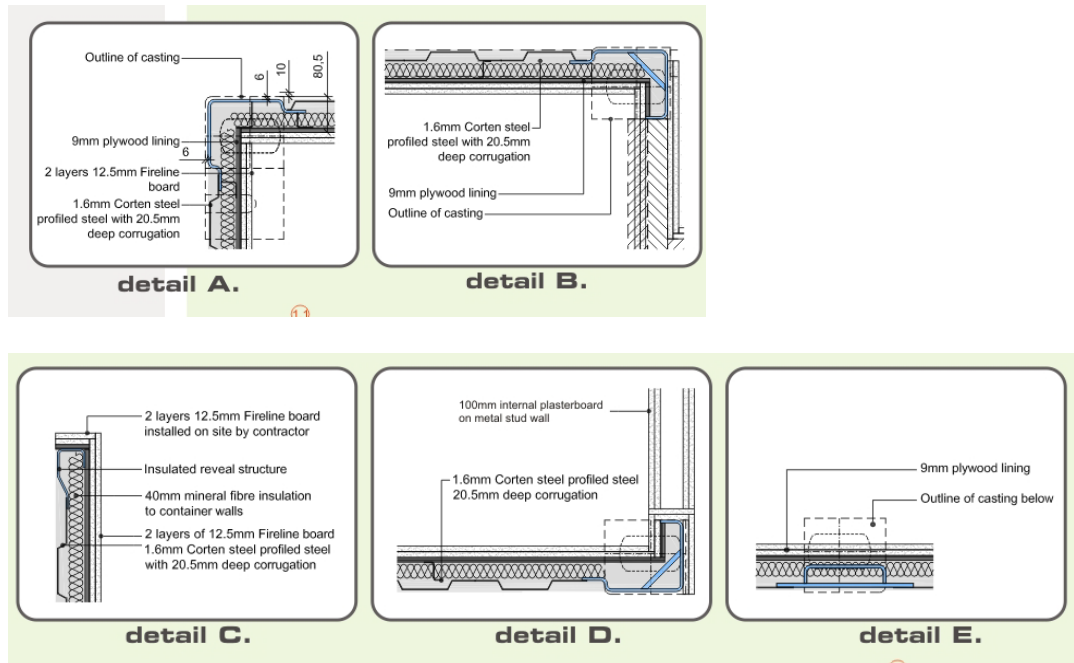


Figure 4.31 Standard ISBU container product details

4.3.6 STANDARDISED HOTEL BUILDING PRODUCT

In 2007 an international passenger air carrier approached the product development team to develop standardised hotel buildings for airport destinations in Europe. The ‘pan European’ brief, negotiated through the product briefing meetings started as a product proposal for a 100-150 bedroom hotel in standard sized container units. The ISBU would be based on the optimum dimensions for manufacturing and shipping of 1.5 x width 40ft container (3.5 m x 12.2m) and in 2009, a fitted-out and furnished prototype module manufactured in China was shipped to the UK. See Figure 4.32.

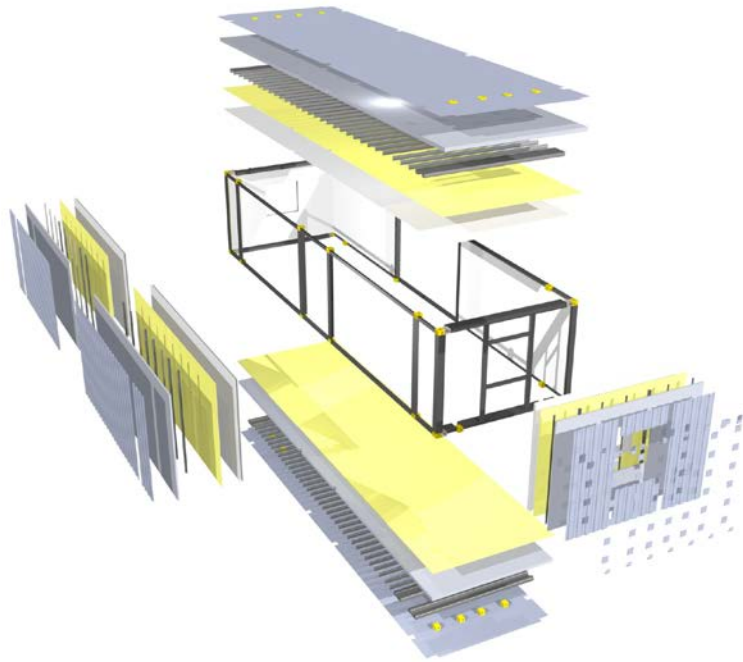


Figure 4.32 Standard ISBU container product (source: KKA architects)

The intention for the standard building product was not only to standardise the units, but also to maximise the degree of off-site manufactured elements including ground floor frames, risers, cladding and roofing as show in Figure 4.33. However, product development stalled with the first project site due to planning laws, which made a standard hotel building unlikely, and the client decided not to continue the project.

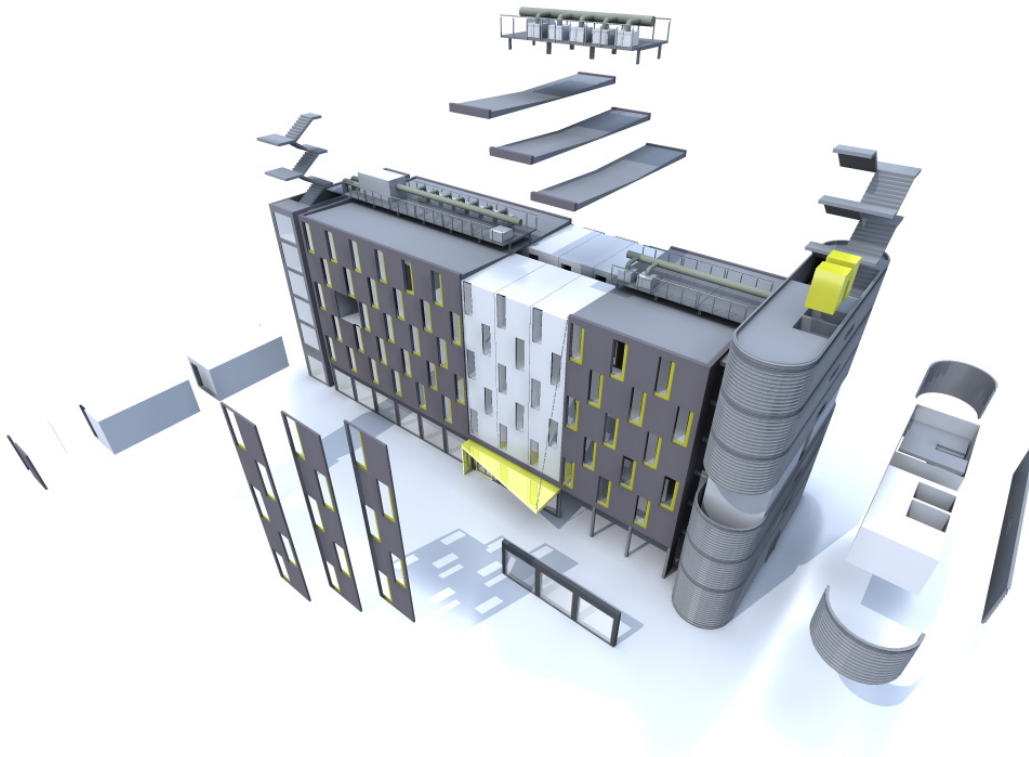


Figure 4.33 Standard hotel building product with off-site manufactured units, frames, risers, cladding and roofing (source: KKA Architects).

The lack of progress on the standard building product meant that the team had to focus on addressing non-standard design conditions: different sized units and local site configurations. However, through the previous projects, many elements of the building started to become standardised. The building elements had been modelled initially using TEKLA, a steel frame modelling programme that could transfer parametric data between the design team and steel frame manufacturer. See Figure 4.34. This had allowed the interfaces between unit types and the steel frame to become linked through this parametric data. Further refinement of the CAD models came with improvements to the BIM on later projects.

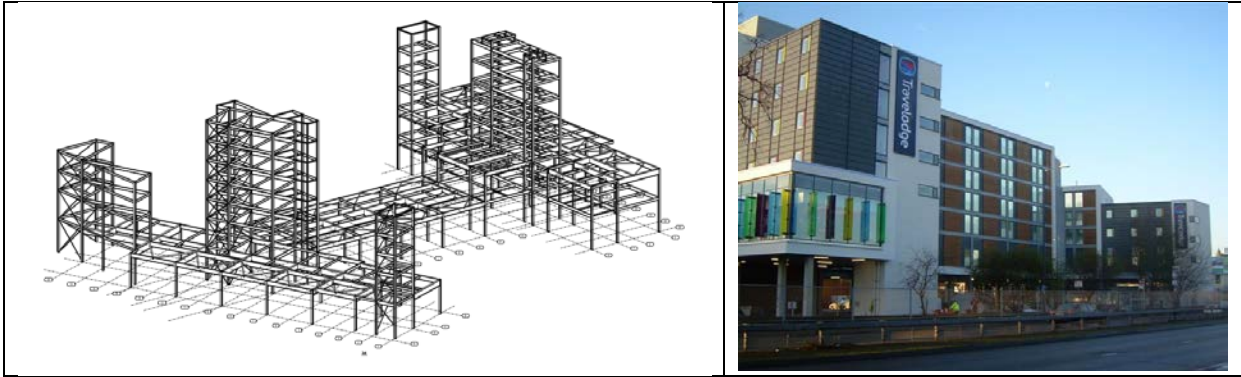


Figure 4.34 TEKLA model for Heathrow Travelodge (source: Buro Happold)

New software advancements in the AutoCAD REVIT program that occurred between 2004-2012 have facilitated CAD models for the units using parametric data. The ability to use data with object orientated representations and scalable building designs allowed the team to create a metric generic building model. The template shown in Figure 4.35 has reference planes in plan and elevation with shared parameter groups of data. This data includes unit dimensions as a function of overall unit sizes, to generate and schedule the required number of units on the building. Within the individual projects further, details were added via reference planes for beam systems and connections.

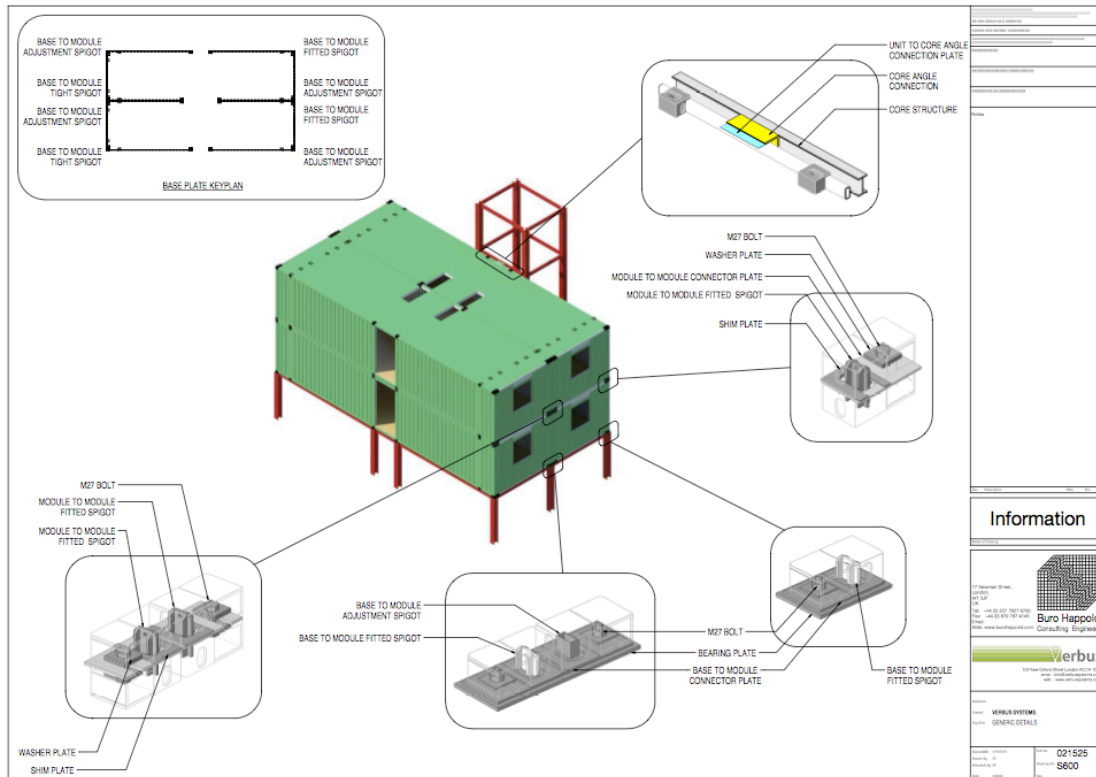


Figure 4.35 Summary drawing of the main parametric elements and details

Three-dimensional CAD models were generated through REVIT and then transferred across to visualisation software to demonstrate the integration of different engineering elements in the building product. See detailed visualisation in Figure 4.36. This assisted in visualising the interconnections of building services with the modules for marketing purposes.

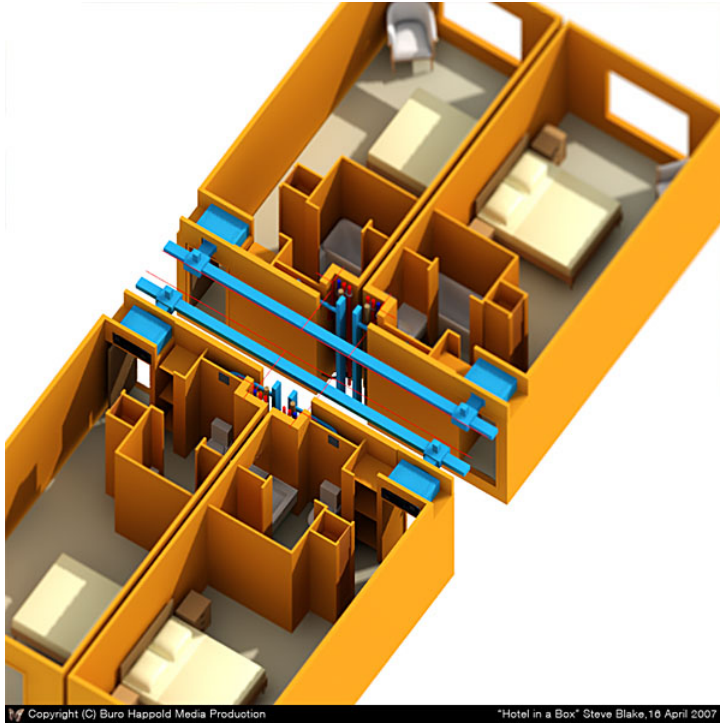


Figure 4.36 Visualisation of the standard hotel bedroom with corridor and vertical riser services used for marketing purposes

The building services design had become more refined and the standardisation of a building allowed this to become more rationalised and established as a standard approach for projects. Issues for internal environmental of the spaces in the building were driven by environmental comfort through temperature control (19-21 degrees C), adequate flow rate for ventilation 10-12 L/s per person, light levels in the bedroom and circulation spaces of minimum 100-150 lux, and standard power and data supplies (CIBSE Guide A 2007, Table 1.5).

Ventilation supply and temperature control in the rooms depended on whether the supply of fresh air would come naturally through either open windows, or a noise attenuated vent directly linked to the exterior wall; or mechanically via ducted air from mechanical roof-top plant supplied through the corridors to the bedrooms. The standard design assumed supply of tempered air from the corridor with local heating and cooling using a fan-coil unit in a void above the main bedroom entrance door. An alternative, lower cost design was to use attenuated vents in the exterior wall with an extract in the bathroom riser, but would depend

on local preference and site issues. The bathroom extract was designed to be powered by fans at the top of each riser at roof level. Figure 4.37 shows the standard supply and extract schematic for the typical floor.

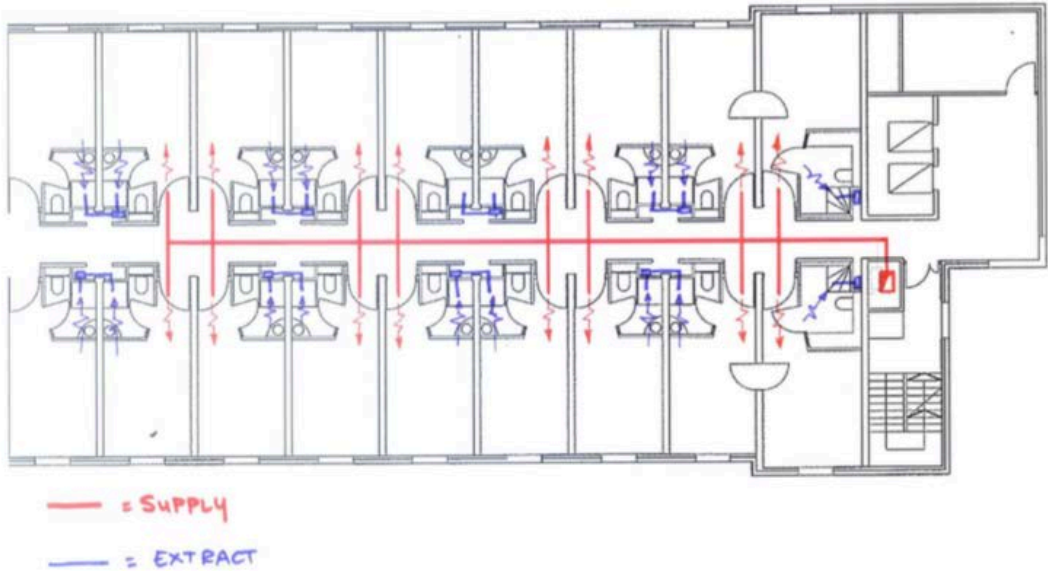


Figure 4.37 Standard supply and extract arrangement on a typical hotel floor

The unit modules had a shared twin riser arrangement back to back in modules as shown in Figure 4.38, with vertical hot and cold-water services, soil stack on one side and twin extract ducts leading to a vertical extract riser on the other side.

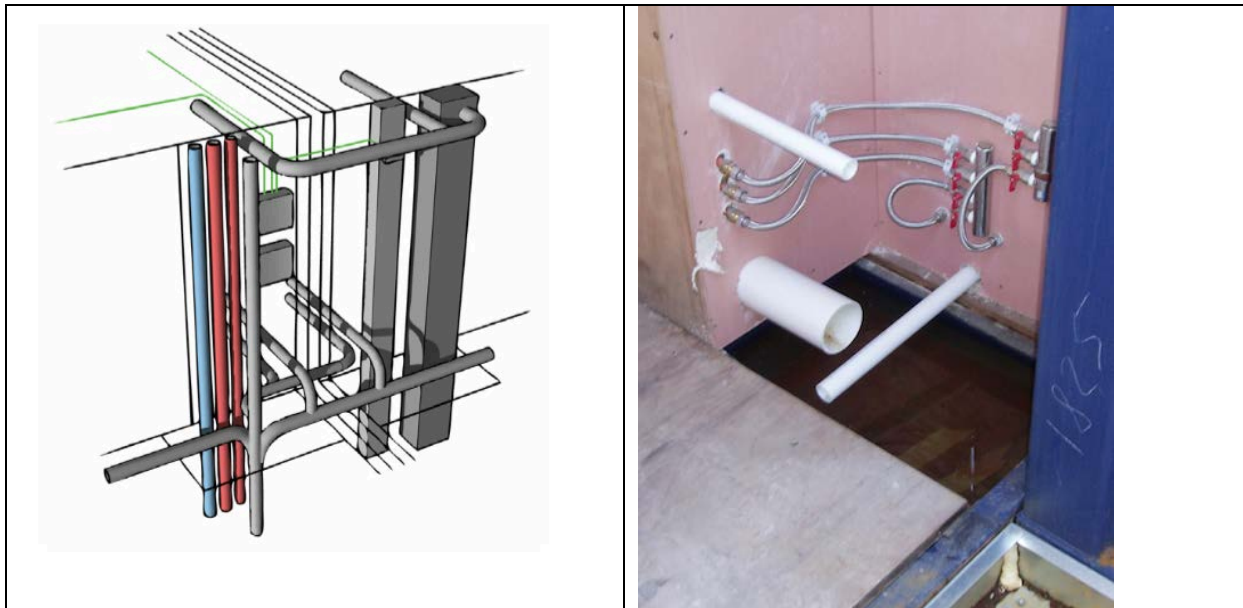
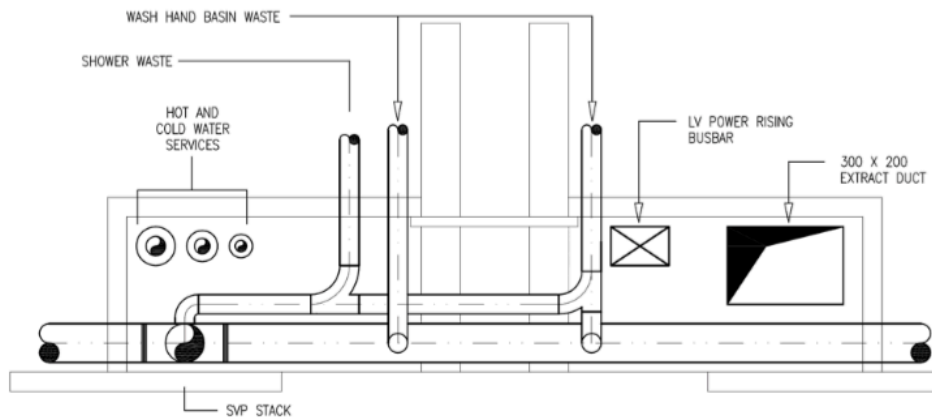


Figure 4.38 Vertical arrangement of hot and cold water services, soil stacks, extract ducts and low voltage power in a twin riser

The design of the integrated riser meant that some of the vertical pipework could be pre-installed with flexible couplings. A decision was also made to line the risers and doors with fire rated material to allow riser installation to be uninterrupted over the full height of the building. Both this method and fire stopping had been attempted in previous projects with the former being the preferred method.

4.4 ISBU ENGINEERING PERFORMANCE (WP 2B)

The units had to fulfil UK building regulations, but for prefabricated units to be certified in Europe, their performance characteristics needed to follow Guidelines for European Technical Approval (ETAG 023).

The term “prefabricated” in the ETAG indicates,

“the products are manufactured using industrial series production or a process similar to series production on the basis of a pre-designed system” (ETAG 2006, Section 2.1 p 9).

According to the guidelines, prefabricated building units are designed as box-like structures assembled in a factory but may be transportable to site in flat-pack or three-dimensional format. They usually comprise a metal frame, or are in metal and timber or concrete. The units may individually form a building or be arranged in conjunction with other units. The purpose of prefabrication is to rapidly provide a weather-proof envelope, but final weathering and jointing between units can be added on site as would connections to services and any foundation connections (ETAG 2006).

The product development team had reviewed the ISBU modules against the Essential Requirements (ER’s) (ETAG 023; Section 6 Table 4, pp. 38-39). Table 4.1 shows how these compare with UK Approved Documents.

ETAG 023 European Technical Approvals Guidelines (EOTA)	
Essential Requirements	UK Building Regulations Comparison
ER 1 - Mechanical resistance and Stability	Part A - Structures
ER 2 - Safety in Case of Fire	Part B - Fire
ER 3 - Hygiene, Health & Environment	Part C - Moisture Part D - Toxic Substances
ER 4 - Safety in Use	Part K - Falling risk
ER 5 - Protection Against Noise	Part E - Acoustics
ER 6 - Energy Economy and heat	Part L - Conservation of Power

retention	
Areas not covered by EOTA	Part F - Ventilation Part G - Hygiene Part H - Drainage Part J - Heat Part M - Disabled Access Part N – Glazing

Table 4.1 Comparison of ETAG essential requirements with UK Approved Documents

4.4.1 STRUCTURAL CAPACITY

Calculations on the unit were made to EN 1993-1-1 (2005): Eurocode 3. The generic calculations were set up for different configurations of building heights and number of units and wind loads. The container unit was analysed as a structural steel frame with infill panels, all in Corten A Steel with a yield stress of 375 N/mm²

Vertical load & stability had been calculated for loading combinations of vertical dead, live load and wind load, to assess vertical load capacity of corner columns/panels and sway stiffness of panels. Compression resistance of the corner posts, 150 x 170 x 6 mm folded sheet corners, as shown in Figure 4.39, are restrained against buckling in two directions by corrugated wall panels, see Figure 4.40, and by taking into account stiffness of top and bottom rails. The calculated maximum capacity was 1078 kN.

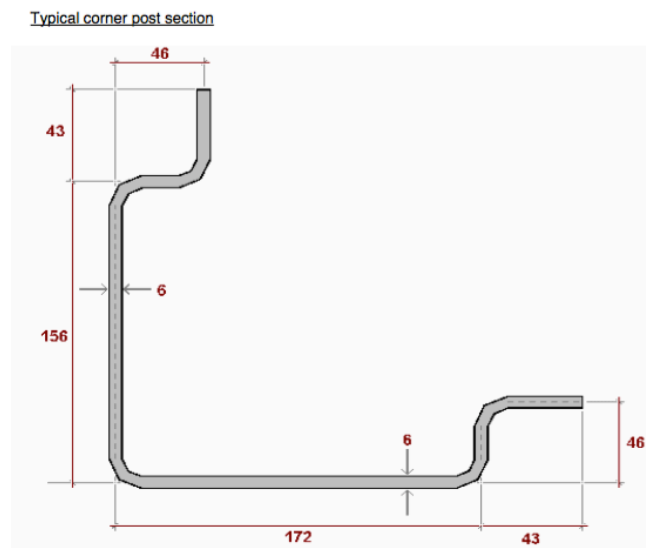


Figure 4.39 Corner post section profile in 6 mm steel restrained by corrugated sheet (not shown) (source: Buro Happold)

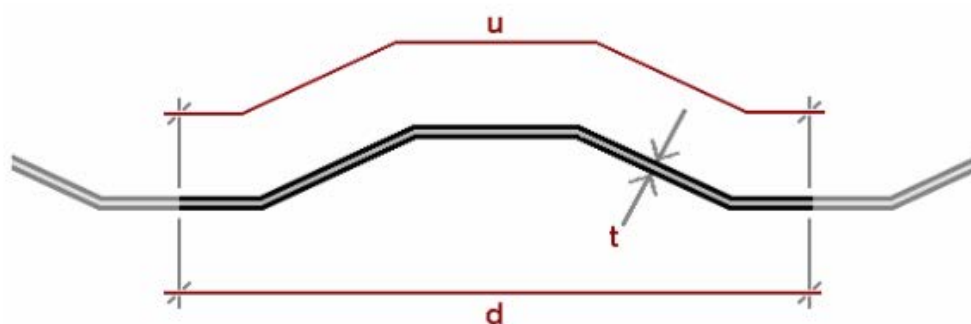


Figure 4.40 Corrugated panel section used to establish pitch (d) against length of corrugation (u)

The effective stiffness of the corrugated panels was calculated using BS5950: Part 9, taking into account panel thickness (t), corrugation pitch (d), length of corrugation (u), Young's Modulus E and Poisson's Ratio ν for steel. The panel section was 1.6 mm steel plate with 278 mm pitch corrugations. An equivalent bending stiffness from this analysis was used to calculate deflections on end panels under wind loads. The ultimate shear capacity in the panel was also calculated and the corner posts were checked for deflection and additional axial loads due to combined effects of wind load and vertical loadings. The central part of each end panel was ignored to allow for the possibility of a full height window. See Figure 4.41.

End Panel Resisting Wind Loads

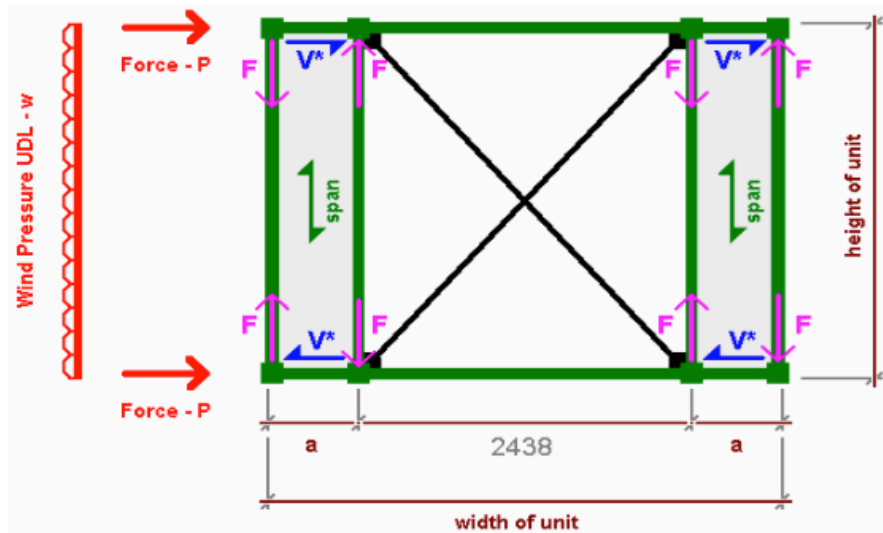


Figure 4.41 Diagram showing assumed distribution of wind load into shear panels

The robustness against disproportionate collapse for the stacked units was checked to Euro code EC1 – Part 2.7 using the scenario-based approach. The assumptions regarding loss of corner panel or internal panel are similar to strategies outlined in SCI Publication P302 for Modular Construction using Light Steel framing. This led to the design of the horizontal and vertical tension connections between units with the critical component being a horizontal link place with a capacity of 44 kN as shown in Figure 4.42.

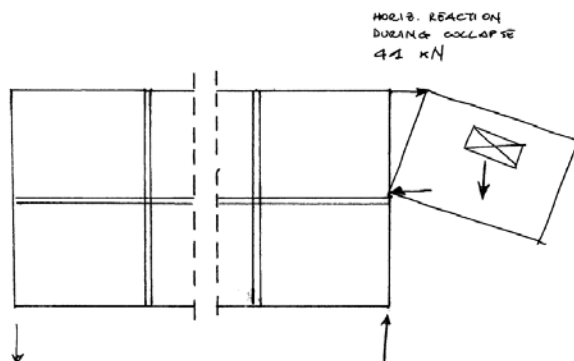


Figure 4.42 Loss of vertical support to end unit leads to horizontal tie-force loads in adjacent containers

4.4.2 STRUCTURAL TESTING

There were two sets of structural testing on prototype units. The purpose of the testing was 1) to prove the capacity of the units through non-destructive testing in order to comply with ISO 1496-1:1990 for intermodal transportation, and 2) to test the ultimate load capacity of a single prototype unit.

A housing prototype unit under a stacking test load of 96,000 kg had a maximum bowing of the corner post of 0.75 mm and under transverse and longitudinal loads of 1524 kg and 7,620 kg the top of the unit deflected by 3mm and 12.5 mm respectively.

In anticipation of their first project, Verbus/G&H ordered a 13 unit run of 20 ft. containers from the CIMC factory. See Figure 4.42. A unit for multi-storey construction.



Figure 4.42 Production of first run of containers for multi-storey construction

The first of these units was load tested on a larger rig as shown in Figure 4.43 to prove a calculated maximum capacity on a unit corner post for 13 storeys of stacked units under

vertical loads in combination with generic horizontal wind loads. The corner post and intermediate side post were then tested to 145 Tonnes and 90 Tonnes. Detailed results of these tests were not accessible to the researcher, but other documents record that the container withstood the loads with permanent deformation and the load capacity of the testing rig was reached before an ultimate failure load was recorded. The results of this test were used to refine the analysis of the containers and the calculated ultimate load capacity as outlined in the previous sections.



Figure 4.43 Load testing of the multi-storey unit prototype

4.4.3 FIRE PERFORMANCE

Overall fire performance of buildings are driven by: levels of occupancy, use, height and floor area, approaches to protection, compartmentation, means of escape, fire spread through walls and windows, flammability of finishes and accessibility for fire-fighting. For accommodation buildings, up to 18 m building height, a structural fire resistance is 60 minutes. From 18 to 30 m height 90 minutes resistance is needed, and above this height fire resistance needs to be 120 minutes.

Similar to steel frame construction, the sheet metal and frame of the containers needed to be protected by plasterboard to achieve 60, 90 and 120 minutes fire resistance. A level of redundancy in the container structure gave an opportunity to reduce the layers of fire protection by verifying that a reduced strength in the supporting structure would still be sufficient to carry the building loads. The plasterboard also has a role in isolating acoustic transmission and in view of the measured performance in the first modules as outlined in the next section, it was decided that it was possible to reduce the layers of plaster boarding in the ceiling.

The fire performance was justified by calculating the theoretical temperature gradient, using a thermal model to calculate residual strength of the units under fire conditions. A parametric fire curve based on Eurocode 1 and interpretation of BS 476: Part 21: 1987 for site-specific fire exposure conditions, avoided a more conservative application of BS 476. In general, hotel bedrooms have a low fire load and the use of the parametric curve assisted in reducing the fire protection when a 90 minute building was under consideration at Hull.

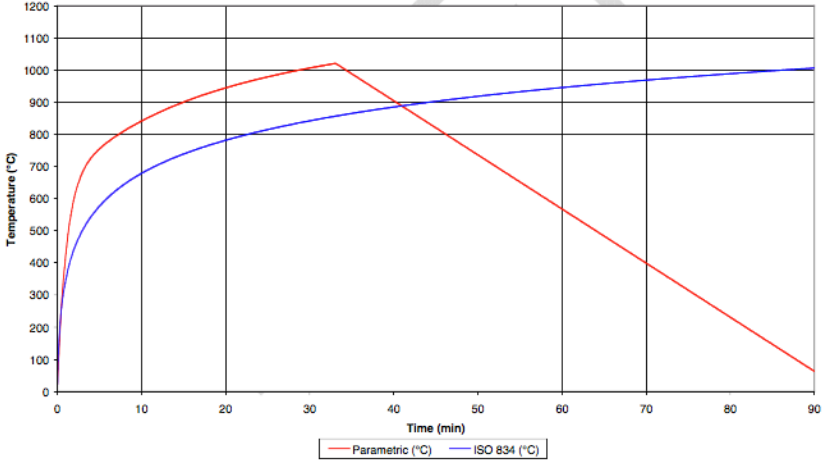


Figure 4.44 Parametric fire curved compared to standard fire curve.

Figure 4.44 shows that the calculated fire based on the fire load burns more intensely at the start compared to the standard fire curve temperatures, but diminishes much sooner, as after only 30 minutes the fire load in the typical bedroom had burnt out. The fire resistance in the units was able to be equivalent to a 60 minute fire rating by taking into account of the drop-off fire intensity and duration.

4.4.4 ACOUSTIC PERFORMANCE

Airborne sound transferred between walls and floors for residential rooms according to Part E of building regulations must not exceed minimum values of 43 dB ($DnT_{1w} + C_{tr}$) and 45 dB ($DnT_{1w} + C_{tr}$) for floors and stairs. Any wall must also have a minimum sound insulation of 40 dB R_w . Transmission of impact sound between floors must be less than 62 ($L'nT_{1w}$) dB. In accordance with Approved Document part E, any building must have pre-completion testing of 10% of each separate habitable room/dwelling type constructed, for airborne sound insulation and impact sound resistance.

For the prototype house module, a minimum design was assumed for designs as shown in the section in Figures 4.44 & 4.45.

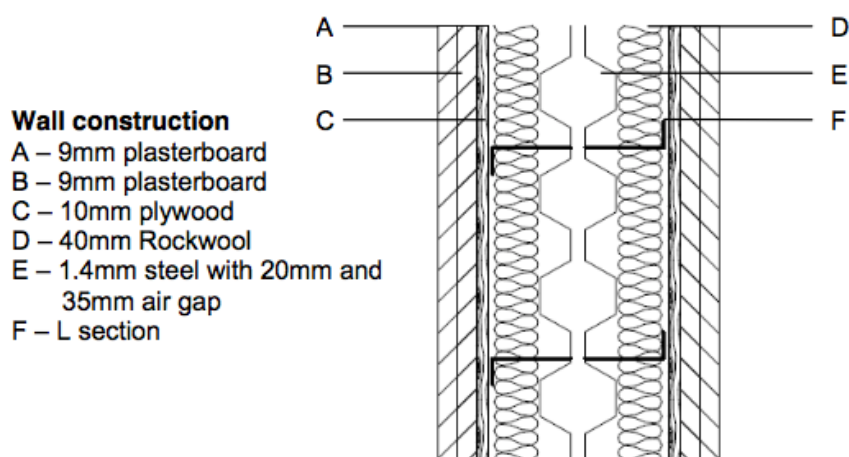


Figure 4.44 Wall to wall detail build up assumed for acoustic design (source: Buro Happold)

Measured values of transmission ceiling to floor in the prototype house were 60-62 dB (DnT_{1w} + Ctr) with 30 (L'nT_{1w}) dB for sound impact.

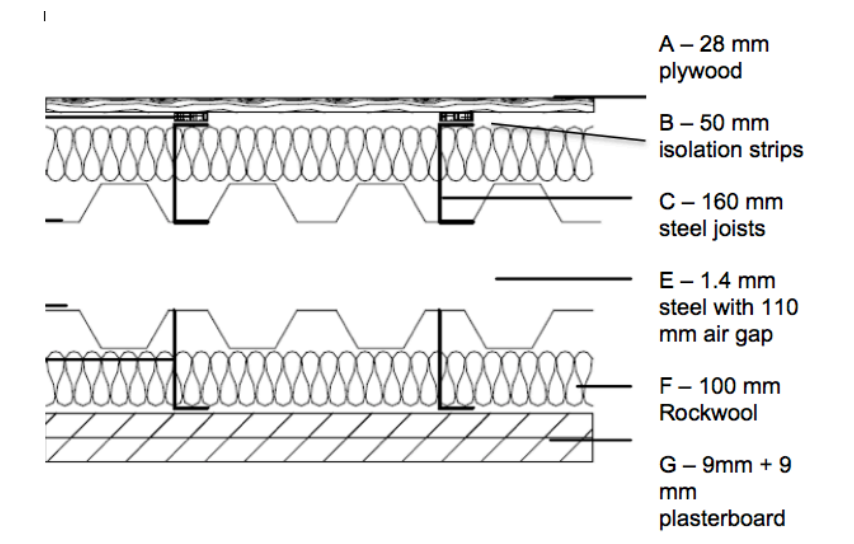


Figure 4.45 Floor to ceiling build-up assumed for acoustic design (source: Buro Happold)

Insitu testing in the first hotel building was carried out in 3 rooms (10% of floor area) as shown in Figure 4.46.

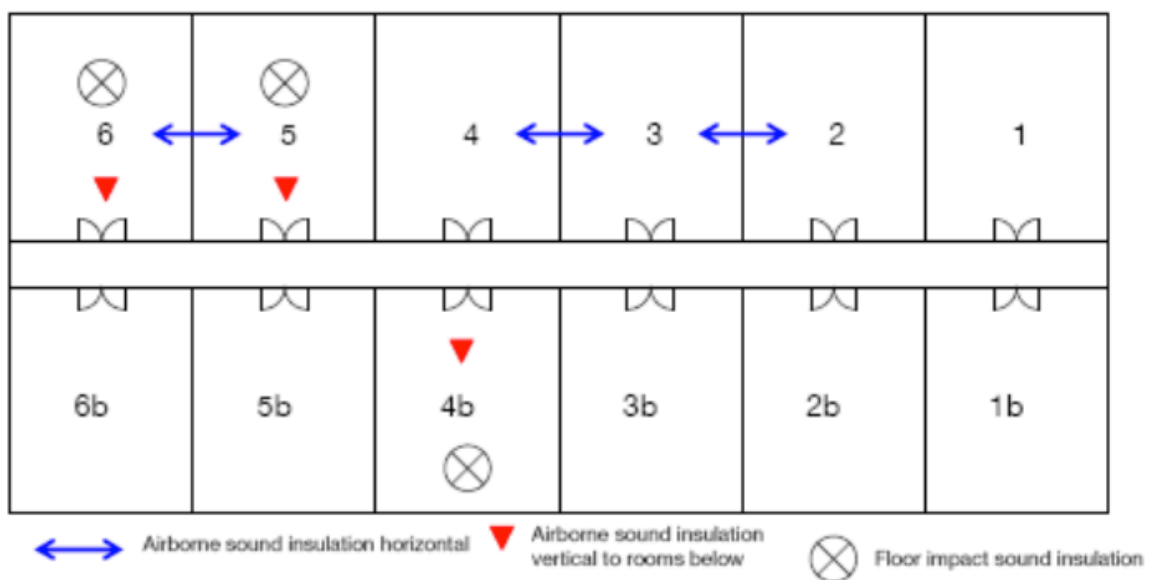


Figure 4.46 Layout of acoustic testing in first prototype building installation (source: Yates et al 2007)

The test results demonstrated that airborne sound insulation was in excess of 50 dB ($D_{nT_{1w}} + C_{tr}$) wall-to-wall and greater than 54 dB ($D_{nT_{1w}} + C_{tr}$) floor to ceiling.

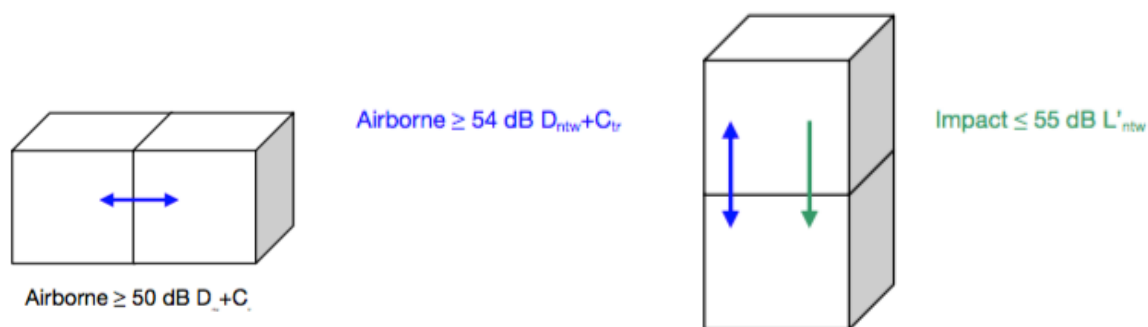


Figure 4.47 Measured transmission of air-borne and impact sound between adjacent units (source Buro Happold)

Vertical airborne sound insulation was tested to be in excess of 54 dB $D_{nT_{1w}} + C_{tr}$ and impact sound less than 55 dB $L'_{nT_{1w}}$. See Figure 4.47. A more detailed account of the acoustic testing has been published in Institute of Acoustics Conference Proceedings 2007 (Yates et al 2007).

4.4.5 CARBON FOOTPRINT ANALYSIS

Re-using existing containers for construction is widely seen as more sustainable than new-build construction techniques, which makes containerised construction synonymous with green architecture (Kotnik 2008). However, there is no published data on the carbon footprint of containers. During ISBU product development, the carbon footprint was calculated using figures from DEFRA, Inventory of Carbon and Energy (ICE) 2011; other carbon footprint calculators are now more widely available, but at the time that the analysis took place the

design team had chosen to use DEFRA figures due to the availability of detailed breakdown figures for carbon emissions.

For the carbon footprint analysis, generic building designs for a conventional steel framed building were compared with the figures for the new ISBU modules from China, for re-used containers, and light steel modules sourced in the UK. Figures were compared for structure, finishes and fittings in the modules. Other building elements, including services, cladding and circulation were considered the same for comparative methods.

As outlined in Paper 2, later BIM models could generate material schedules for use with other data. However, at these initial development stages, the BIM models were still being refined and so manually measured data was combined on a spread sheet based LCA tool. Configured using DEFRA (2010) figures for carbon emissions; the carbon footprint of the containers from raw materials to factory gate and site gate could be estimated, although only to within an estimated accuracy of +/-25% due to the approximate values of the DEFRA figures.

A scenario was set for the construction of a 5 storey, 100-bedroom hotel in the Midlands, UK on concrete piled foundations with brick cladding. The total building consisted of 70 modules arranged over a total area of 3075 m². The modules were completed and fitted out in Guangdong Province, China and shipped from Hong Kong over 15,000 km to a port in the southeast of England and then transported 300 km by road to the site. The corresponding light steel module frames were assumed to be 40% lighter than the container modules and were transported 250 km by road to the site. The concrete for the substructure was sourced from the Midlands and the steel work from North Wales. Carbon factors (DEFRA 2010) were applied for materials extraction and processing using figures in Table 4.2. Transport

rates were 0.0000161 kgCO₂/kg/km for shipping and 0.000984 kgCO₂/kg/km for road transport (DEFRA 2010).

Materials	Carbon Factor (tCO₂/kg)
Steel plate	0.00166
Concrete for piles C35	0.000119
Reinforcement – piles & ground slab	0.0014
Concrete for ground bearing slab C40	0.000133
Plywood (no bio fuel)	0.0011
Mineral Wool	0.00128
Plasterboard	0.00039
Linoleum	0.000121
General Steel	0.00146
Ceramic	0.00161
Laminated veneer lumber	0.00065

Table 4.2 Carbon factors (DEFRA 2010) for materials extraction and processing

Paper 2 (Appendix B) concludes that the largest saving in carbon is found with re-used ISBUs. An ISBU fabricated in China and brought to Europe has a higher carbon footprint than a competing light steel equivalent fabricated in Europe. However, with modules only accounting for 40% of the overall typical carbon footprint, comparisons between volumetric systems have a reduced effect. The biggest difference in the study was the measured difference between new and re-used modules.

4.4.6 FURTHER INTERVIEWS ON APPROACHES TO PRODUCT DEVELOPMENT

Three second stage interviews were carried out on members of staff at Buro Happold to clarify some of the approaches previously adopted for product development. Those interviewed had been involved in the BAA building product projects and other design practice work involving construction product development. During first stage interviews, parallels had been drawn between the container product development work and cladding systems.

Cladding systems are products developed previously and were therefore supplier driven in their designs and installation.

An interview with the facade engineer revealed that there are two routes to product development and procurement in the cladding industry. The first is through manufacturers who work on highly bespoke systems. These systems are based on a common set of principles, and may incorporate standard components but their application is novel or innovative, and designs are based on the basic principles of cladding performance. This approach usually involves the testing of a new construction product prototype. The alternative route is to work with a highly standardised system with minimal scope for adaptation. This route does not involve construction product prototyping beyond the manufacturer's initial product testing. However, what was unexpected was the discovery that there are few instances of projects between these two extremes.

“Customisation is always very small scale. Why would you do that? These things have been developed for one type of use, and to alter them.. you introduce risk by changing the way that a product was intended to be installed; a Wycoma (popular cladding) system with the joint moved.. from its usual below slab position.. (can lead to) leaks, and the manufacturers aren't interested in providing a warranty” (Engineer C2).

Products in between the standard and bespoke solutions tend to be rare, due to the limitations of liability outside a previously tested set of performances. With a bespoke design, there is an expectation of some experimentation, product prototyping and improvement, but product designs deviating from standardised performance specifications are rarely adopted due to product liabilities.

4.5 ISBU PRODUCTION STRATEGIES (WP3A)

As part of the research into production and procurement strategies the research looked for links between manufacturing models, degrees of pre-assembly and modes of procurement.

The container hotel case study buildings were compared with similar repeat projects for a hotel operator that used other methods of construction. In Paper 4 these two sets of case studies were outlined and compared for their supplier-driven and client-led characteristics. All the ISBU modular container projects are known to be supplier driven and the City Inn projects were proven to be client driven.

The research used quantitative methods to measure the extent of preassembly in the modular construction projects. To do this, definitions for levels of preassembly had to be refined, and these are shown in Table 4.3.

4.5.1 MODULAR PRODUCTION STRATEGY MEASUREMENT

Paper 3 (Appendix C) describes in more detail the breakdown of the sequential development of the projects. After the initial product prototyping of the modular construction units, the product development process occurred through incremental changes in subsequent projects. The original goal of the manufacturer had been to develop a standard building product that was made-to-forecast (MtF) to maximise efficiencies of scale in production as normally encountered in container manufacturing. The data on the five containerised construction buildings showed that the product was being developed with many of the components and preassemblies made to order (MtO), but only raw and processed materials and some small components were being made to forecast. The 'New Product Development' model in Chapter 2 for routine commissions, with well defined briefs and standard solutions needs adjustment to model the situation in the case studies investigated. The design was interdisciplinary for repeat projects, but the product could not be made-to-forecast (MtF), since even for the most standard volumetric elements there was still a design to order and make to order element. The

only elements that could be made to forecast appeared to be the raw and processed materials needed for the on-site work.

	LITERATURE DEFINITIONS		TERMS ADOPTED FOR THESE STUDIES
	Definitions of On-site and Off-site Construction	Manufacturing Production Strategies	Building Fabric Materials and Products
0.	Raw and Processed Materials (Fox et al 2001; Eekhout 2008)	Made to Forecast (MtF) (Winch 2003) Also known as 'Made to Stock' (Eekhout 2008)	Structural Steel: hot-rolled plate and profiles, cold-rolled steel coil, and bolts. Reinforced Concrete Structure: ready-mixed concrete, concrete paving, and standard lengths of reinforcing bar. Structural Timber: standard lengths and panels of structural timber and plywood Masonry Construction: ready-mixed mortar, standard bricks, blocks and lintels. Cladding: standard sized glass panels, glass blocks Partition Walls: standard plasterboard sheets, rolls of insulation.
1.	Components (Also referred to as 'loose parts') (Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	Made to Order (MtO) (Winch 2003)	Structural Steel: fabricated hot-rolled steel sections, castings and connections, fabricated cold-formed steel elements. Reinforced Concrete: pre-bent deformed steel bars, sleeved connectors, stop-ends/pull-out bars. Structural Timber: pre-cut timber and boards, Masonry Construction: special bricks, blocks and lintels. Cladding: clamp and stick system cladding, glass panels. Partition Walls: non-standard plasterboard and insulation panels.
2a.	Subassemblies (Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	Made to Order (MtO) (Winch 2003)	Structural Steel: pre-welded and bolted steel frames, pre-formed cold-formed steel frames. Reinforced Concrete: prefabricated steel reinforcement cages, hybrid pre-cast concrete elements for further casting on site (e.g. twin-wall and 'Omnia' slabs) Structural Timber: timber stud panels, structurally insulated timber panels (SIPS) Cladding: framed glass panels, rain screen cladding. Partition Walls: plasterboard and insulation panel assemblies.
2b.	2D Non-Volumetric Preassemblies	Made to Order (MtO)	Structural Steel: insulated and boarded steel frame panels.

	(Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	(Winch 2003)	Reinforced Concrete: pre-cast concrete panels and slabs. Structural Timber: insulated timber frame panels.. Cladding: panelised glass cladding, composite insulated panels and curtain walling, complete frame assemblies.
3.	3D Volumetric Preassemblies (Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	Made to Order (MtO) (Winch 2003)	Structural Steel: insulated and boarded steel volumetric assemblies. Reinforced Concrete: pre-cast concrete volumetric assemblies. Structural Timber: insulated timber frame volumetric assemblies.
4.	Pods (Gibb & Pendlebury 2006)	Made to Order (MtO) (Winch 2003)	Fully serviced small, enclosed assemblies, non-loadbearing, in timber, steel and composite panel, e.g. bathrooms.

Table 4.3 Definitions of on-site and off-site processes for construction products as adopted in the research

Quantities in tonnes of different levels of preassembly were measured and displayed in percentages of total weight in a graphic to show flow of materials from producer to manufacturer to site. See Figures 4.44 and 4.45.

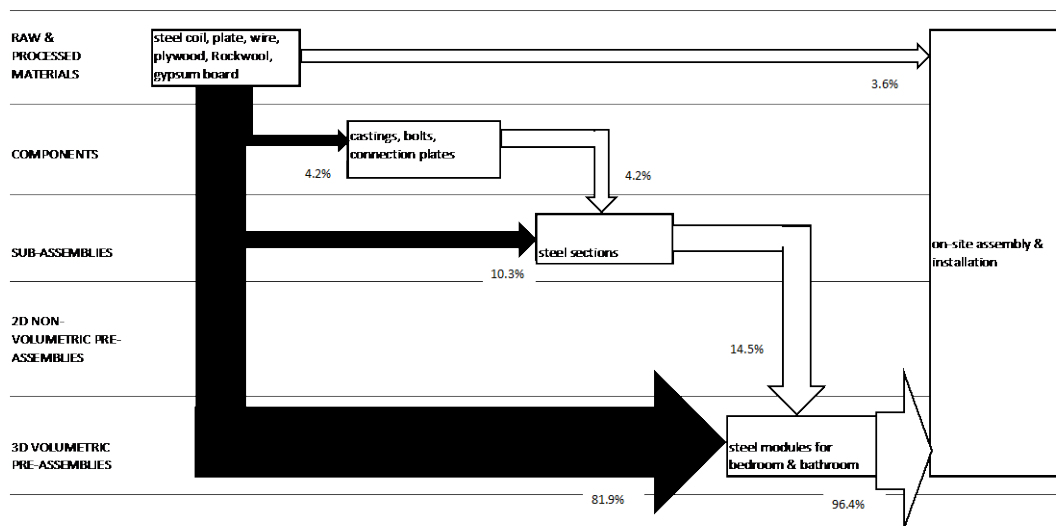


Figure 4.44 Materials flow for typical Case Study A1 – Volumetric steel bedroom modules with integral bathrooms (source: by author)

Figure 4.44 shows the degree of off-site output ISBUs used in the hotels. Almost all the structure is preassembly (96.4%). 82% of raw materials are sent directly to the container factory, and 14.4% are components and subassemblies from other manufacturers, added to the ISBUs before they are delivered to site. The remaining 3.6% are fittings and on-site addition of make-up pieces between modules. The units eventually had complete interior finishes and fittings, but the corridor sections where most of the distribution pipes and ductwork were located were finished on site.

4.5.2 NON-MODULAR PRODUCTION STRATEGY MEASUREMENT

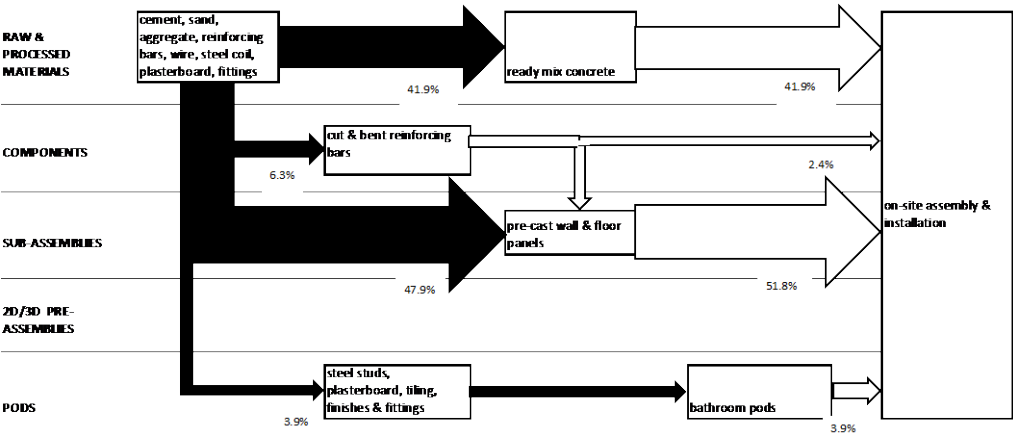


Figure 4.45 Material Flow for typical case study B3 – Hybrid precast/insitu concrete room with bathroom pod (source: by author).

Figure 4.45 contrasts with Figure 4.44, which shows the degree of on-site work for an insitu/precast wall and slab solution. Data shows 41.9% of structural raw materials (concrete, loose reinforcing bars) plus pre-bent reinforcing bars delivered to site. These are combined with concrete panel sub-assemblies (52.8%) from the pre-casting manufacturer, to form walls and floors of the bedrooms, with bathroom pods added fully assembled off-site.

4.6 ISBU PROCUREMENT STRATEGIES (WP3B)

WP(4) uses further data from the ISBU case studies and similar hotel buildings procured and built using other methods to compare the extent of supplier-driven and client-led designs. The research demonstrates how project conditions influence the supplier-driven scenario using project data and project team interviews, in order to develop an overall picture of procurement conditions against production strategies

4.6.1 INTERVIEW DATA

Interview data came from project teams working on hotel buildings similar to the Verbus projects. A group of engineers were working on a series of hotels for a single client, City Inn and they developed an approach for three consecutive hotel buildings in the UK in Manchester, Leeds and City of London.

Designers for both sets of projects were interviewed; this identified the commoditised nature of the volumetric modules compared to non-volumetric designs. The research found that repeat-order clients are prepared to consider longer term value through an off-site supplier-driven system, but with suppliers only being able to offer part of the building solution, clients still chose to use a main contractor as a single point of commercial risk for the projects. This means that the other barriers encountered for off-site construction, particularly the challenges of procurement and longer lead-in times result in a combination of on-site combined with off-site (hybrid) methods being adopted. There are also inherent limitations on the standardisation of buildings due to their site-specific requirements. Building solutions that combine more balanced aspects of on-site and off-site techniques could provide one solution for dealing with the challenges of procurement and standardisation.

4.6.2 RESEARCH OUTCOMES

The research confirmed previously identified tendencies between procurement and levels of standardisation, and there were further observations on characteristics and trends of supplier-driven designs. In the case studies investigated, suppliers were not offering a product that could adequately replace the conventional project commission and design process. In all cases the product was a partial solution, and clients did not enter into a direct order with the supplier without a main contractor on board. In some cases this resulted in a late order for the building units, adding some uncertainty to the selection of manufacturer and the detailed design of the building to accommodate the units. Research documented in Paper 4 concludes that a balanced approach to off-site and on-site using more flexible methods can ease some of the tensions encountered with manufacturing lead-in times due to delayed procurement.

5 BUILDING DESIGN PROTOTYPE DATA (WP 4)

5.1 INTRODUCTION

Data for this analysis of framing and building design prototyping was drawn from project documents, drawings, reports, reviews and semi-structured interviews. The engineering team was divided into five groups: a modular design team of 40 designers, and four station teams, each consisting of 15-20 engineers. A sample of 25 project participants was identified to cover the range of roles and responsibilities. Although the sampling frame relied mainly on the engineering team, the lead architect and project QS were also interviewed. Each interviewee was assigned a letter (from A-Y), and these used in the coded results and discussion sections that follow.

Interviewee	Type
A	Structural Engineering Associate (Prototype Team)
B	Structural Engineering Associate (Prototype Team)
C	Building Services Discipline leader (Prototype Team)
D	Fire Engineer (Prototype Team)
E	Building Services Associate (Station Team)
F	Building Services (Station Team)
G	Building Services Director (Prototype Team)
H	Building Services Associate Director (Station Team)
J	Structural Engineering (Station Team)
K	Building Services, Senior Engineer (Station Team)
L	Lead Project Director
M	Project Partner
N	Façade Engineering Director
O	Lead Architect
P	Lead Quantity Surveyor
Q	Structural Engineer (Station Team)
R	Mike Parkinson (Lift Designer)
S	Project Manager (Station Team)
T	Lead Structural Engineer
U	Infrastructure Director
V	Project Management, Director

W	Infrastructure Associate
X	Structural Engineering Associate (Station Team)
Y	Project Manager (Prototype Team)

Table 5.1 Interviewees and team roles

5.1.1 PRELIMINARY INTERVIEW ANALYSIS AND QUESTIONNAIRE

Following the project close-out review or ‘After Action Review’ (AAR), core research themes were chosen for the interviews as set out below. As part of the extended reviewing process, the findings from the interviews were summarised and presented back to the project teams in a questionnaire. Most points raised in the interviews were about project delivery (22) and design (20). The remaining themes were related to collaboration (15), information technology (7), finance (11) and commercial issues (6). The main points were collated and summarised into detailed questions and given to 73 members of staff. There were 81 questions put to the team based on the interview findings and 23 staff (33%) responded to the survey.

The following issues for each core theme were raised in the interviews and subsequent questionnaire.

1. **Project Delivery** - issues of organisation, leadership (Project and Discipline), understanding of brief, programming and management of work, co-location of office, and management of client and stakeholder relationships.
2. **Design** - issues of design strategy (modularisation/standardisation), standards, consistency, duplication of work, management of information, division of work between offices and regions, and integration of specialist consultants and sub-consultants.
3. **Collaboration** - issues of multi-disciplinary working, cross regional/office working with F+P, DL and other consultants, and client.
4. **Technology (IT)** - issues of the use of BIM, Buzz saw, and SharePoint and other design and technical collaboration tools and systems

5. **Finance** - issues of allocation of fees, financial management – accounting for month and final profit, project and group performance, disparities between groups, project vs. group/region accountabilities, control of costs (resources)
6. **Commercial** - issues of management of change from client and architect, and clarity of contractual scope.

The interview data identified that brief definition, design standardisation and the application of the modular designs had been challenging for the project team, with the review highlighting some important learning points. In particular interfaces between the station designs and preceding packages were not handled very well and the design team underestimated the complexity of the brief and its interpretation with the client.

A sample of statements in the questionnaire relating to project delivery are given below.

There was too little over-lap between (the station work and preceding) packages and important information was missing from the brief that was needed to design the stations in detail.

Strongly Agreed / Agreed:	84%	Neutral:	16%	Disagreed / Strongly Disagreed:	0%
---------------------------	------------	----------	------------	---------------------------------	-----------

(The architects) did not interrogate the brief in a systematic way and the (design) management team overestimated their (the architects') ability to assimilate the brief requirements.

Strongly Agreed / Agreed:	85%	Neutral:	15%	Disagreed / Strongly Disagreed:	0%
---------------------------	------------	----------	------------	---------------------------------	-----------

Once the brief had been assimilated and agreed, the process of applying a modular pre-design to several stations also brought its challenges to the design; in particular the degree to which modular elements could be applied across all areas of the stations was under question and this was an issue for both the structural design and building services installations. These issues were overcome in part by a rigorous and methodical approach to communicating the design principles between the different parts of the team, particularly design change.

The principle of modularisation worked well for the platform designs. The station concourse areas could not be modularised and a 'kit of parts' approach with a set of common details was used instead.

Strongly Agreed / Agreed:	57%	Neutral:	19%	Disagreed / Strongly Disagreed:	24%
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There were limited opportunities for standardisation of the (building services) design in the different stations due to 'local factors', including local environmental conditions, plant room locations and differing building scales and capacities.

Strongly Agreed / Agreed:	58%	Neutral:	21%	Disagreed / Strongly Disagreed:	21%
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Design notes were the most effective way of defining the design principles. Design principles were agreed at fortnightly meetings. These dropped off during the later stages of the project.

Strongly Agreed / Agreed:	79%	Neutral:	21%	Disagreed / Strongly Disagreed:	0%
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5.2 ILL DEFINITION, PROBLEM/SOLUTION FRAMING AND DESIGN CO-EVOLUTION WP(4A)

5.2.1 DETAILED INTERVIEW ANALYSIS AND CODING OF DATA

Having previously identified in literature the importance of ill definition, framing and building design prototyping as important issues for the research, the interview and questionnaire data, with the aid of Nvivo software, was coded on these topics, and individual transcripts were selectively coded to formulate propositions on the research.

As outlined in Paper 5, three aspects of brief development and problem solving were detected in the interview data: 1) ill definition, 2) boundary framing (Schön 1983; Atkin 1993; Paton & Dorst 2011) and 3) problem solving/use of typologies. Brief development and boundary framing are described further in this work package and problem solving/use of typologies has been described further in following work package WP 4b.

5.2.2 ILL DEFINITION & FRAMING

At the preliminary design stages, the prototype team's objective was to: "... convert the client's brief into a working document." (Designer P; Prototype Team). The concept report specified design criteria, zoning of the station areas, their operation, with benchmarked costings. It had nine initial options for platform and concourse configurations and outlined the principles for a modular design. However, to complete the concept report the brief required some re-interpretation by the design team.

"There is a written brief ... It describes what the station should encompass,... but there are no standards. It's a description of functions, and missing certain things out. A lot of detail on certain things and missing others completely." (Manager Y; Prototype Team).

The client had provided a document that was detailed in many aspects, but also ill defined (and in some cases undefined). For example, the links between the station design and other packages for rail infrastructure were incomplete, and there was insufficient information on the operational requirements for the stations. The station configuration and layout was being driven by passenger movements, and in the absence of the complete data, and in order to model people flow accurately, the design team engaged their own specialists:

"As part of the team, we employed a pseudo operator [name removed] who .. worked out staff numbers, accommodation... number of passengers and how to operate the station, since it wasn't really known. That was a major risk for the joint venture." (Designer A; Prototype Team).

There were also changes made in the brief. The client had originally specified segregated platforms for boarding and disembarkation.

"...every train had an arrival and departing platform, that was questioned quite early on, and towards the end of concept design, ... there was a change in brief from the client.. (It) was quite a big change to the brief when we were already two months in, but it was the right thing to do." (Designer B; Prototype Team).

The initial arrangement of trains and platforms with separated boarding and disembarkation had proved too costly.

The change in brief that occurred during the latter stages of the concept design stage appeared to be a necessary part of the design process; the client needed the design team to develop their preferred configuration in order to verify whether or not it was affordable. Eventually a shared level strategy was adopted for the detailed design.

“...it wasn’t until we started detailed design ... (that) we started to talk about front of house (and) back of house areas...; it’s a fairly key strategy... (there was) a debate about whether to have two levels in the atrium or two separate buildings with link bridges... from the upper levels down to the platforms... A lot of those issues got discussed a huge amount.” (Designer E, Prototype Team).

However, the circulation spaces had to be re-designed to deal with issues of shared arrival and departure routes. The complexity of the more affordable shared spaces option led to a re-design of the station support areas to deal with a sequenced flow of arrivals and departures passengers.

5.2.3 FRAMING AND DESIGN CO-EVOLUTION

Paper 5 identifies how framing in these instances where the project brief and project solution were evolving and this has been compared to the co-evolving theory model for the design problem/solution resolution as described in Chapter 2, repeated here in Figure 5.1.

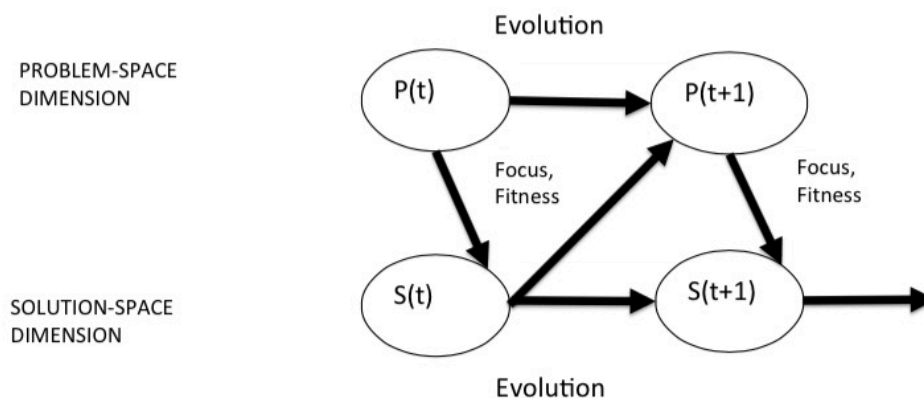


Figure 5.1 Co-evolutionary design for ill defined problems & solutions (source: Poon & Maher 1997)

This co-evolutionary theory model is useful for describing the changes in design commission design outcome as encountered in this case study. In co-evolutionary terms, the refinements to the station operation in the brief and the resulting solutions are the episodes in problem and solution space in the model, with the focus/fitness being the design activity where the two are reconciled and checked between each other. The benefit of defining these problems and solutions as co-evolving is to assist in the identification and partial structuring of ideas, and this is what happened through the application of pre-designs to the new station designs.

Due to the case study involving a pre-design, some of the ill definition could be solved in a design prototype phase of the design, and although some ill definition is inevitable, by using the idea of pre-designs in the co-evolving design model (Poon & Maher 1997), it is possible to shorten the later phases of repeat designs; this is similar to the concept of partial structuring by Dorst & Cross (2001). So, Figure 5.2 combines a pre-design with a detailed design, which is a novel development. The detailed design may be repeated several times based on the generic prototype, as is the situation in the case study later. Importantly, in the co-evolutionary model, the design prototyping (Gero 1996) process eliminates some initial stages of problem and solution definition. Furthermore, the combined model shows the prototype stage as mostly problem driven, and the execution stage as mostly solution driven.

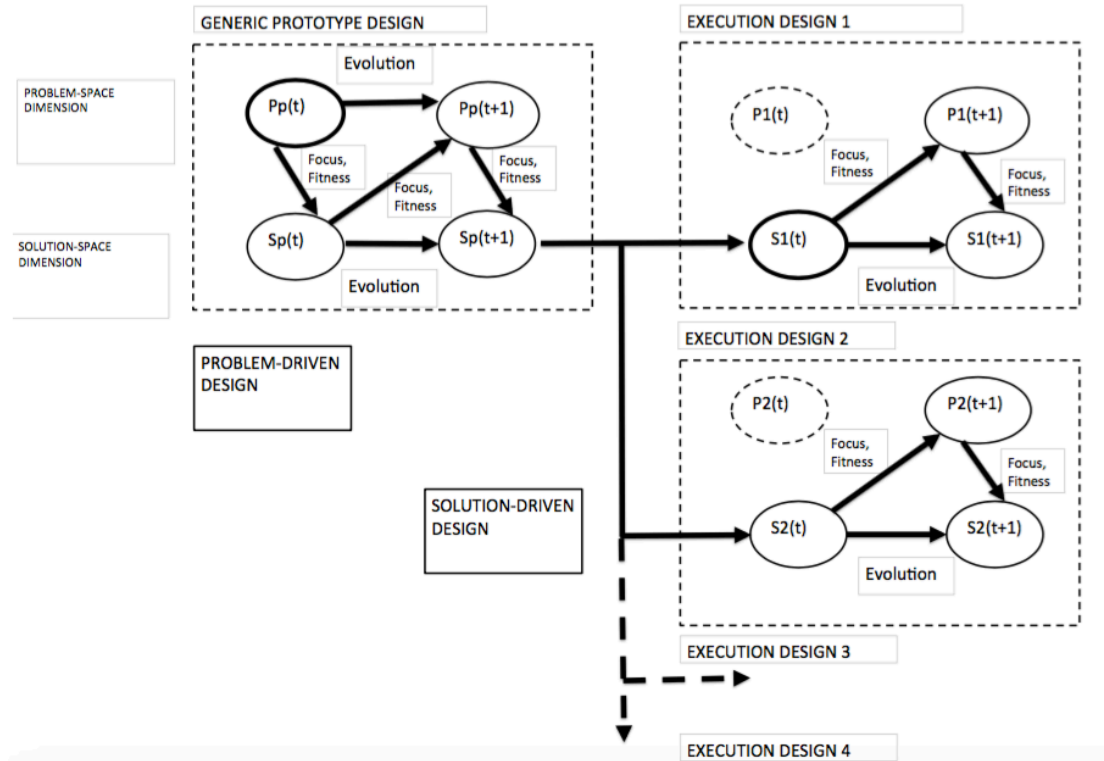


Figure 5.2 Co-evolution of problem-solution in prototype design prior to multiple execution designs (source: by author based on Poon & Maher 1997)

5.3 LINEAR/NON-LINEAR DESIGN PROCESSES, AND BUILDING DESIGN PROTOTYPING (WP 4B)

The final part of this research describes how the systematic model of conceptual design prototyping was applied to modular station designs, by first identifying the type of design processes being used in order to assist in differentiating the different conditions of design problem. Based on literature, the types of design process are either linear (Pugh 1990; Cross 2006) or non-linear (Lawson 1994) as outlined in Chapter 2 and Paper 5.

In the previous part of this research (WP 4a), the brief was ill defined and the problem and solution co-evolved (Poon & Maher 1997). This research now compares the initial prototype

design and subsequent development with the creative and innovative stages in a prototype model.

5.3.1 BUILDING DESIGN PROTOTYPING

Figure 5.3 shows a combined model for design prototyping based on Gero's (1996) theory models in Chapter 2. Gero describes three conditions of design linked to prototype generation, adaptation and application for creative, innovative non-routine and standard routine designs (Gero 1996). In this stage of the research, prototype instances as used in the pre-designs are sorted to match these different conditions.

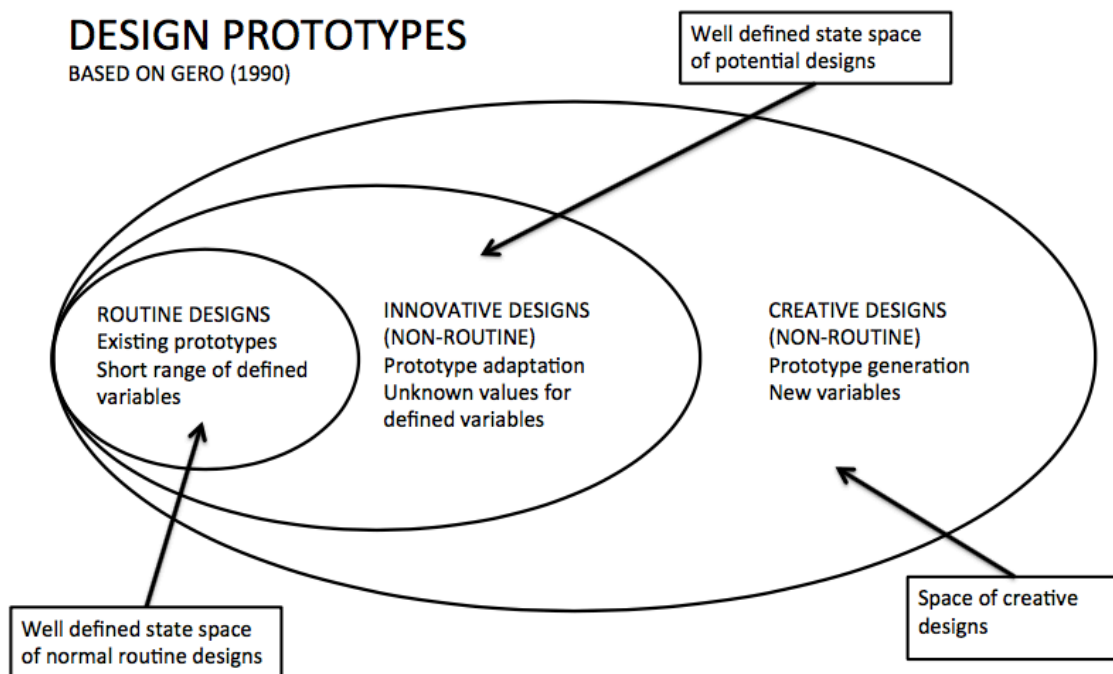


Figure 5.3 State spaces of routine, innovative and creative designs (source: by author, based on Gero 1996)

The client for the high-speed railway had commissioned the design of four new stations, to be designed in nine months. Each station had 7-8 rail platforms and would cover an area of 50-70,000 square metres when built. There were a number of site-specific issues linked to the location of the stations in built-up urban areas. Following a limited design competition, the winning team proposed to design the four rail stations simultaneously, using a prototype design with modular elements to meet the short timescale. Judging that site-specific design issues could be resolved through subsequent adaptations of the prototype, the team proposed a repeated design:

“...the theory of the project..(was) one building design, four locations.” (Project Director M; Prototype Team)

“... they (the prototype team) did a great job of setting the principles..., if there was ever a job that lent itself to ‘cookie-cutter’ design it was this (project).” (Designer Q; Station Team).

A consistent feature of the roof design was the principle of uninterrupted clear spaces, as adopted in airport terminal designs (Zunz et al 1990). With all the usual suspended ceiling services distribution removed from roof, the roof becomes a prominent feature of the spaces and clarifies way-finding. With the designers aspiring to create a new rail station archetype, the airport typology was an obvious starting for the new architectural scheme. Figures 5.3 and 5.4 show the principles of a precedent for Stansted airport roof that was used by the team as an initial design model for the station roof.

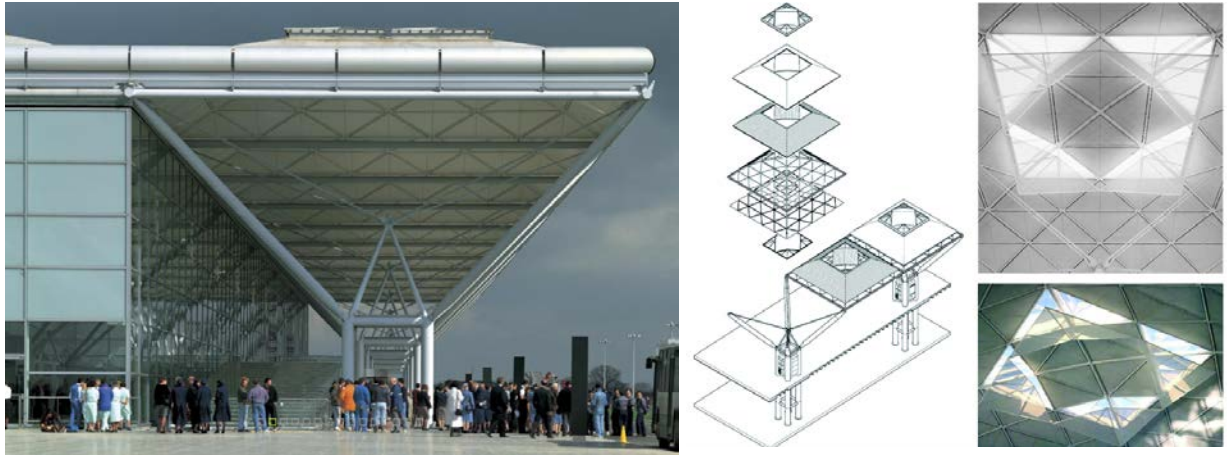


Figure 5.3 Stansted airport roof module (source: Foster & Partners)

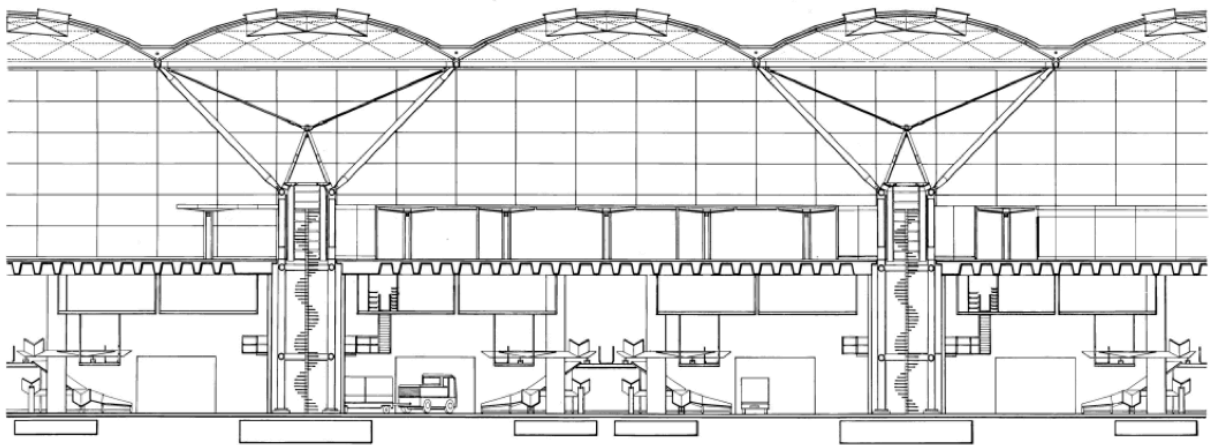


Figure 5.4 Stansted airport building section (source: Foster & Partners)

5.3.2 MODULAR ROOF PRE-DESIGN

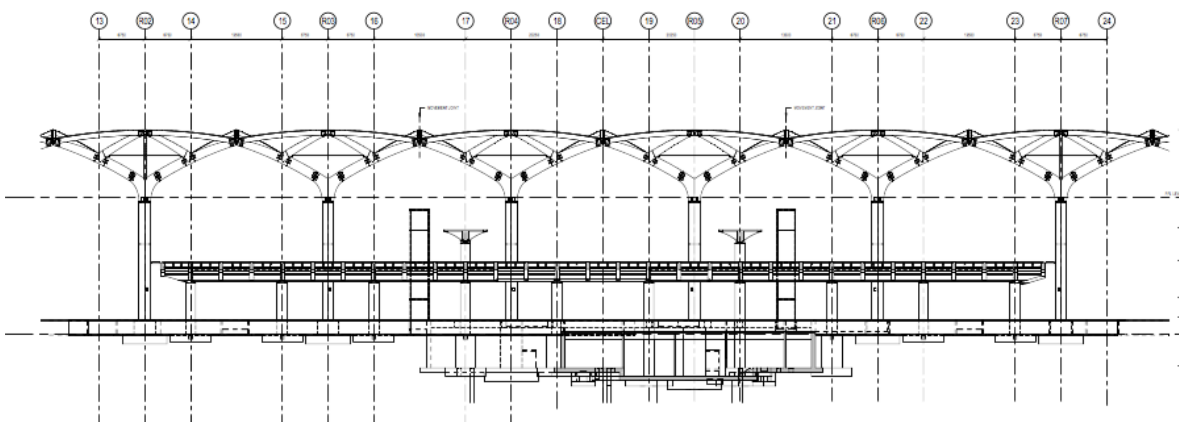


Figure 5.5 Station concourse canopy section

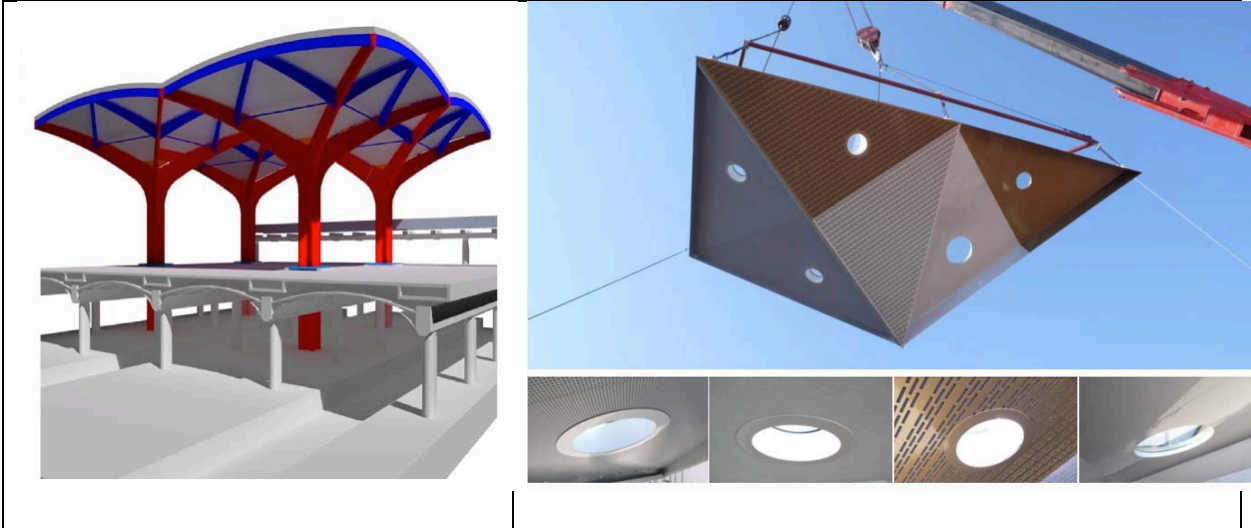


Figure 5.6 Station Canopy design and GRP roof product prototype

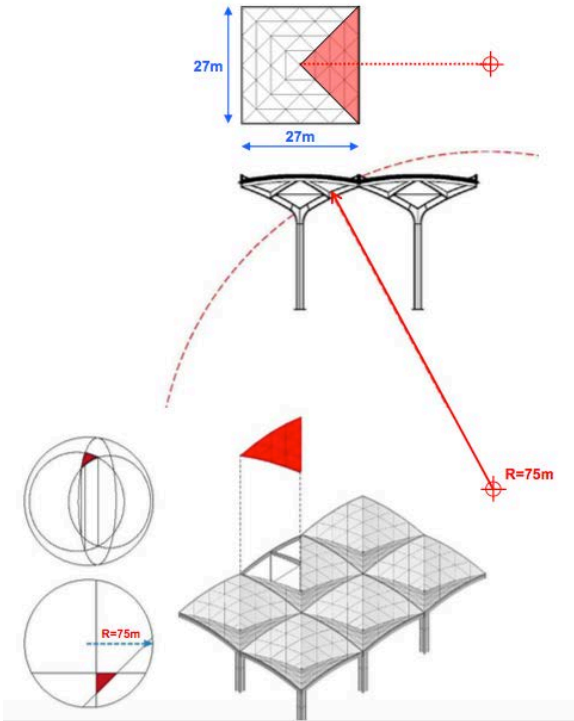


Figure 5.7 Canopy module geometry (source: Buro Happold).

Figures 5.5 to 5.7 show the canopy elements above the platform structure. These were developed on a standard 13.5 m regular grid module with variations to deal with different end conditions. The canopy had three module types, a corner, edge, internal module, with two

column head types, with nine arm sub types with varying thickness of steel to deal with variations in structural loads, particularly temperature expansion.

Arguably, the airport archetype had been the prototype for the station and Figure 5.8 shows where this is positioned on the Gero model. However, the lead architect believed that the modular design approach, although similar to the Stansted roof, was not just a standardised design, particularly as the buildings were adapted to different conditions.

“..the stations do not need to be the same, it is a question of adaptability of the module to all the stations to look different.” (Lead Architect O; Prototype Team).

The airport roof had been highly standardised, but this roof was being adapted to different site conditions and contexts. The creation of the design prototype was non-linear and a result of problem structuring and solving. Modularity as an architectural design device was used in the project to control variety. It still became a unifying design philosophy and a prototype design was defined to be applied across the four stations, but each of the station designs was a combination of applied prototype design and adapted designs based on principles defined through the prototype.

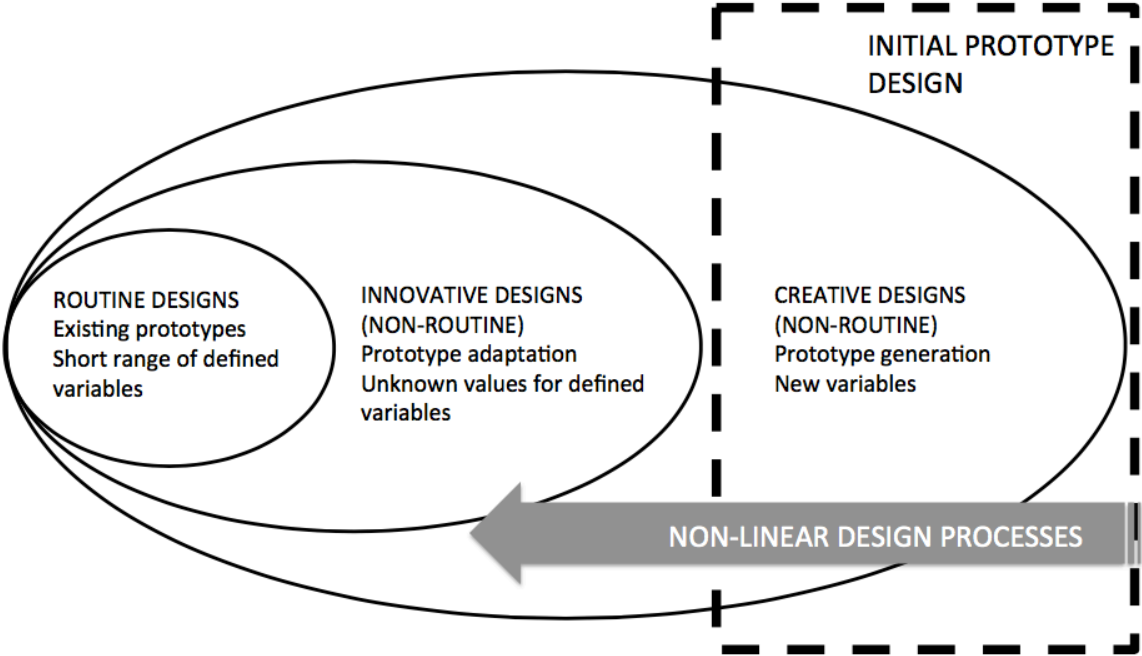
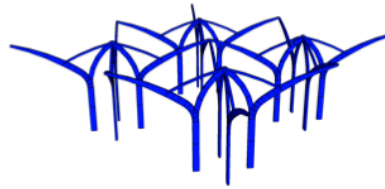


Figure 5.8 Prototype generation (source: by author based on Gero 1996).

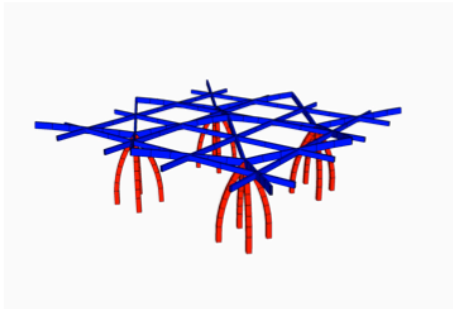
Up to 80-90% of the station structures were deemed to have a definable set of repeatable elements and the structural design was the result of multiple design options and a sample of these is shown in Figure 5.9 including steel and concrete solutions in a number different shapes. Chosen solution was steel cantilever design with a tie-back similar to Option 1 B as shown.



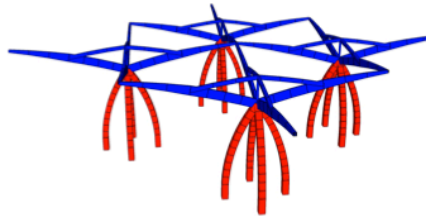
Option 1A Concrete main arch members tied back to a central 9m x 9m arch



Option 1B Steel main arch members tied back to a central 9m x 9m arch



Option 2A Rotated cladding support system and horizontal perpendicular members acting as ties and beams



Option 2B Inclined ties struted down to the crown of a concrete arch

Figure 5.9 Roof design options for steel and concrete roofs in different configurations

This design process once a decision had been made on the materials, involved a structural optimisation of the frame, and was a linear design process.

5.3.3 MODULARISATION AND KIT-OF-PARTS

The project had been set up to allow a modular pre-design to be developed ahead of the design of each rail station building, and this model of pre-design was compared with Gero's (1996) design prototyping model. The linear and non-linear design processes used respectively analytical and conjectural design processes and this helped to identify instances where the pre-design allowed the design to become a more rationalised and analytical and where the designs, despite a pre-design, were less rationalised and more conjectural.

The platform design had fully repeatable design elements that could be modularised into definable complete independent assemblies.

“The platforms were pretty much similar, 400m long, along with the roof modules and platform modules. A fairly strict modular design was carried through, similarly for the main roof concourse for arrivals and departures.” (Designer B; Prototype Team).

Diagrams such as these were used in reports and design memoranda to communicate the prototype design to the rest of the team as shown in Figure 5.10.

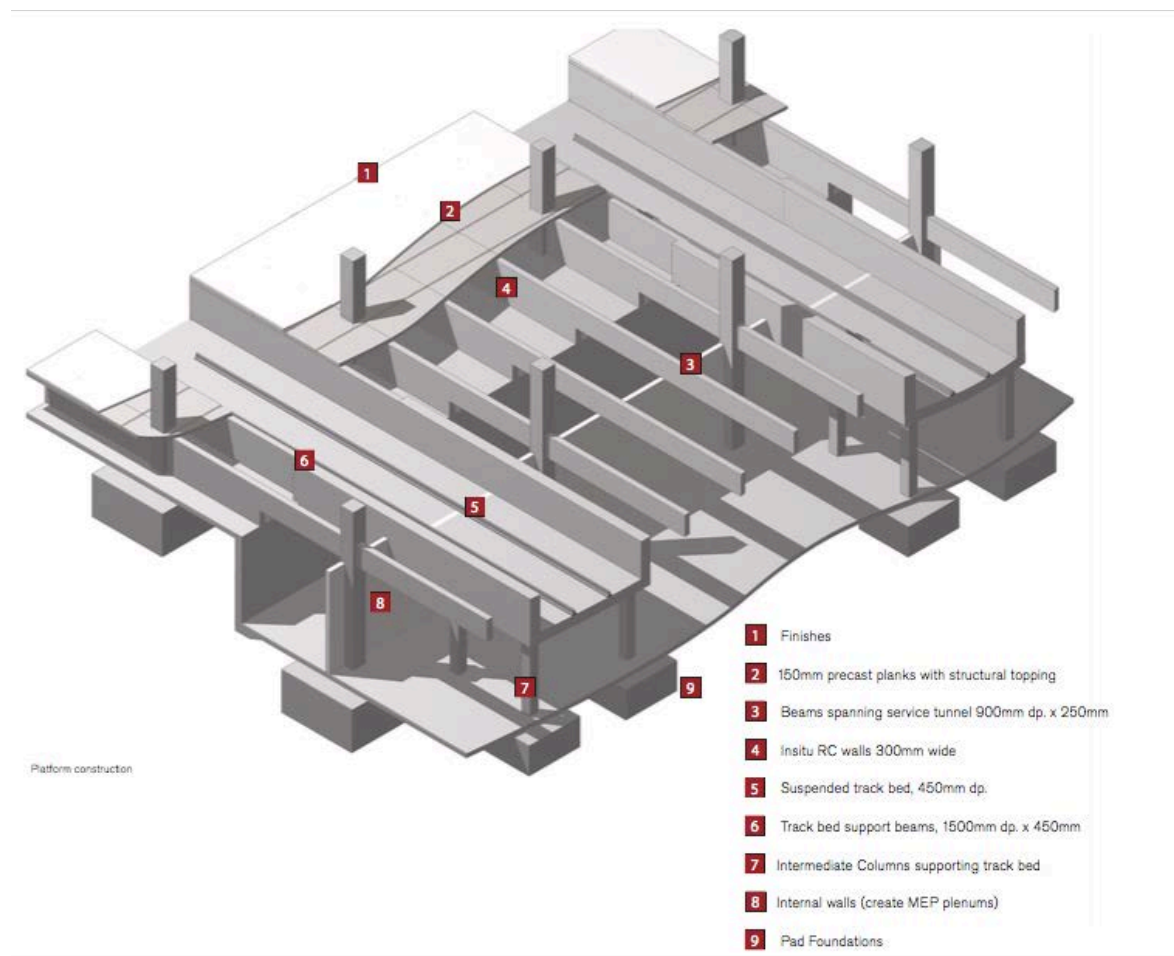


Figure 5.10 Prototype platform arrangement (source: Buro Happold)

Unlike the platforms, the concourses could not easily be translated into a modular design due to passenger numbers and other factors:

The (concourse) is supposed to be modular, but each station has got very different passenger numbers, ... (the) most busy ...with 25,000 people per hour... the south station... has only 5,000.” (Designer B; Prototype Team).

The general arrangement of the concourse was therefore dictated by local site constraints:

“...even with modularity, the differences in (concourse) design were very great..” (Designer Q, Station Team).

As a result, the concourse areas were rationalised into standard repeatable areas in each station and a system of ‘common details’ also referred to as ‘kit-of-parts’ by the interviewees was used as shown in Figure 5.11.

“... (I would say) there were ‘common details’ rather than calling it modular...” (Designer B, Prototype Team).

The team devised a building system of beams and slabs that could be applied as components to the station design.

“... (the designer) who was doing the concourse roof, needed to look at all the station roof drawings.. for the different stations, at each stage, and look at all the different types we had and make sure that all those types were covered.” (Designer A; Prototype Team).

“The analysis model that we received .. was a simplified model which the ..team worked up into station specific model. It had a similar standard kit-of-parts for the (CAD) drawings. Elements were built-up piece by piece. ...it was tricky at the start, knowing where all the pieces went, (and we) needed to know design assumptions made for all the elements (but) eventually it became an incredibly fast tool. (Designer T; Station Team).



Figure 5.11 Concourse element arrangement (source: Buro Happold).

What came from the prototype generation process for the railway stations was a series of solutions with defined variables. In the case of the modular platform structures, which were well defined solutions, the values of those variables had been defined over a short range with fixed elements but variable size and thickness, and the application of the modular designs therefore appeared to be routine. In the case of the component kit-of-parts designs for the concourse areas, the value of those variables was unknown in that the precise arrangement of the components in the stations still had to be worked out, but the variables were defined by the known components. The concourse structures were therefore examples of innovative, non-routine prototype adaptations. Figure 5.12 shows that the repeated modular design became an example of a routine design and the kit-of-parts component designs were non-routine innovative designs.

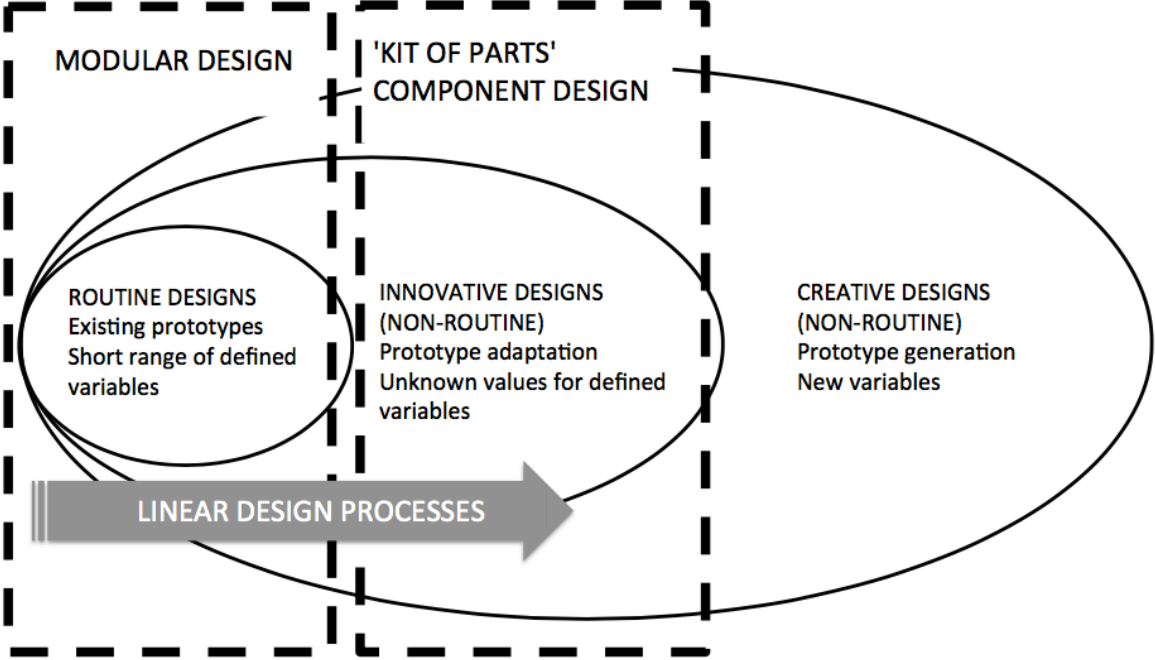


Figure 5.12 Application of routine and non-routine prototype instances (source: by author based on Gero 1996)

However, not all the station design team were in agreement with the task; some expressed concern that they did not feel they had adequate information to address non-standard issues.

For example, one designer noted:

“the problem with the (prototype) design was that we were not party to the design principles. We didn’t understand the details enough. It felt like we were piecing together someone else’s design. We would have had more comfort if someone in the team was involved from the start...” (Designer J; Station Team).

“Even with modularity, the differences in design were very great. Part of the issue was to acknowledge that they were all different.” (Designer D; Prototype Team).

The problem with standardisation is fitting a square peg in a round hole and having many of these. You can only take it so far.... It’s about not being constrained in your mentality. To me this is about an ability to tolerate ambiguity.” (Designer E; Station Team).

Nevertheless, informal conversations with the design team indicated that up to nine man-months of time were likely to have been saved on the design programme as a result of the design prototyping approach. It is pertinent that the design team recognised that, although the prototype did not cover all the design outcomes, the most appropriate approach was to recognise where it could be applied and where further development was needed. Based on a simple analysis of the design drawings, the building structures in each station were 62-71% modular and 25-29% kit-of-parts; the remainder being non-standard. A significant part of the overall station designs was therefore created either directly from the prototype design or from principles defined through the prototype.

6 FINDINGS & IMPLICATIONS

6.1 INTRODUCTION

There have been two aims to this research. The first aim has been to investigate the ISBU product, as developed for multi-storey modular construction (Smith 2010; Lawson et al 2014). The second aim has been to refine design prototyping theory (Gero 1996) as used on modular (Meehan et al 2015) building pre-designs (Lawson 2016), particularly for ill defined briefs (Cross 2006).

The Implications of this ISBU research on academic studies is to provide the first detailed accounts of the product development process for this unique modular construction product. For practice this research gives guidance on the most appropriate uses of the product for future construction projects.

The implications of the work on design prototyping for future academic research is to provide one of the first considerations of this theory in the context of building design. The design theory model can be applied to a range of project contexts, different levels of brief definition and a variety of different design solution types.

This final chapter explains in more detail the key findings from the research and generalises on contributions to theory, with their implications for the construction industry. The chapter ends with a critical evaluation of the studies, and recommendations for further research.

6.2 KEY FINDINGS

6.2.1 ISBU MODULAR PRODUCT DEVELOPMENT (WP 1)

Previous research has identified that dry-freight shipping containers are widely available and their application to construction has occurred mostly through an adaptation of existing units. The standardised nature of the container with sizes and standard fittings makes them attractive for larger-scale mass manufactured use in construction. However, the standard width is limiting in its use for habitation and the wider ISBU module was created to address such issues.

To understand the conditions of their development and use in buildings, the first stage of interviews determined that product development, market placement and commercialisation were the three most important core themes and this shaped the areas of research that followed. Through this initial research it was established that the basic ISO container product was being developed as a more standardised, low-cost, robust alternative to other modular construction solutions.

As the designs were being developed the design team were searching for ways to place the product into the market, either through a supplier-driven contractor design route or through a client-led design route. All the projects were supplier-driven, since the latter would have resulted in much modification to the basic unit, and this contradicted the goals of the manufacturer to produce a basic standard product.

The manufacturing team learned through the early projects that the most viable way to commercialise the product was a focus on value in the contractor's process rather than trying to sell the product at lowest cost.

6.2.2 TECHNICAL PRODUCT DEVELOPMENT (WP 2)

The product development process over seven years began with a prototype for a standard domestic house. A multiple storey accommodation unit of greater than standard container width was built and its configuration tested against existing building case studies. However, it was in hotel buildings that the first ISBU containers were used, as bedroom modules. The majority of the product development, the refinement of the unit structure, connections, and fitting out of the interiors occurred through these first hotel building projects. The manufacturers were focusing predominantly on a robust, standardised unit, and as a result the structural designs were not completely refined. However, this robustness or ‘over-design’ became useful when the modules had to be re-worked on site due to discrepancies in construction.

The first projects involved small production runs of the new module, with non-standard layouts. However, even the larger buildings of 250+ bedrooms had non-standard room sizes due to site constraints. This was because in most cases, the hotel operator wanted to maximise room size on the plot and this led to variable room dimensions.

The structural capacity of the units was established through calculation backed up by some load testing. On-site testing was used in the case of acoustics performance. The structural load tests carried out in China were tests for compliance with ISO standards. The use of different BIM software streamlined the process of design and production of drawings.

6.2.3 PRODUCTION AND PROCUREMENT STRATEGIES FOR ISBU (WP 3)

Despite the very standardised nature of the projects using modular units, coupled with their low cost and economy status, all of the clients opted for a design and build contract with the

main contractor, placing overall project risk firmly with them. In these projects the client had only a marginal interest in the construction method being used. For the non-modular projects the client was very involved and had a direct input on the way the buildings were being procured and built, although they also opted for a design and build contract.

6.2.4 BUILDING DESIGN PROTOTYPING (WP 4)

The purpose of building design prototyping (Gero 1996) is to make approaches to variant designs more systematic. Many building projects are non-routine and the research further investigated ill definition (Cross 2006) and the co-evolving problem-solution model (Poon & Maher 1997; Dorst & Cross 2001) as a way of describing design resolution in these conditions. Any model that attempts to make design processes more systematic as this research has attempted to do, needs to take into account these complexities, and design prototyping (Gero 1996) offers the necessary structure to do this.

Design prototyping formalises the practice for designers creating new solutions or schemas based on pre-designs, that is, generalisations of previous known solutions. The adoption and re-use of previous ideas depends on their contexts. The building design prototyping model provides the terms to describe those contexts, whether they are routine, innovative or creative and whether the briefs are normalised, well defined or ill defined.

In the station case study investigated, there were all three types of solution and context. Some of the repeated designs were intended to be routine, but some needed to be innovative or creative. The station platform and concourse designs were not based on any previously

detailed solutions and included many new designs and their prototype generation was creative and non-routine. The research describes the types of solutions being adopted with some being modular and some being kit-of-parts component designs.

6.3 CONTRIBUTIONS TO THEORY

6.3.1 ISBU MODULAR PRODUCT DEVELOPMENT (WP 1-3)

ISBU modules based on the dry-freight container are a unique product in construction and this thesis compares the product development and engineering performance of this product with known theories on product prototyping.

The research takes previous models for construction, manufacturing and production (Harper 1990; Emmit & Gorse 2002; Winch 2003) and combines these to provide new insights on the relationships between more main-stream manufacturing methods and construction. The studies also use prevailing procurement models to clarify the scenarios being used and how the mostly supplier-driven ISBU modular construction solution has performed compared to non-modular client-led projects.

Figures 6.1 & 6.2 summarise how different levels of preassembly combined with on-site construction are suited to top down client-led and bottom up supplier-driven designs (van Nederveen et al 2010).

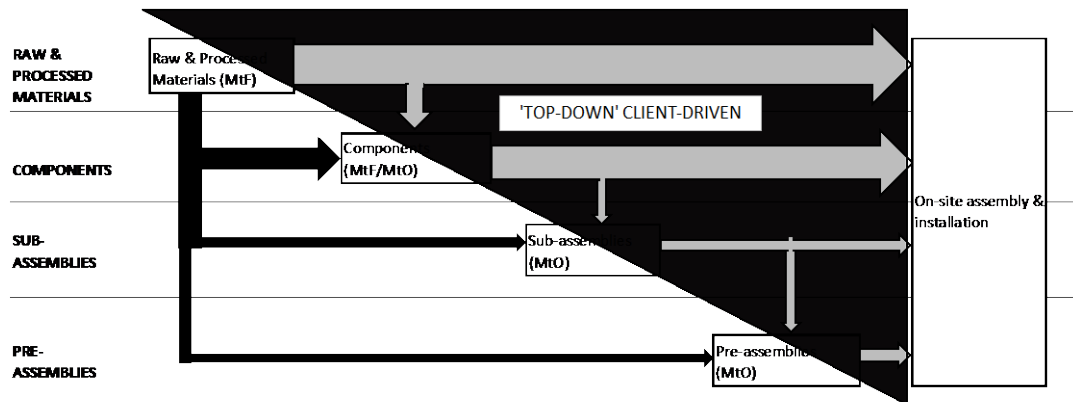


Figure 6.1 Material flows for top down client-driven construction (source: by author)

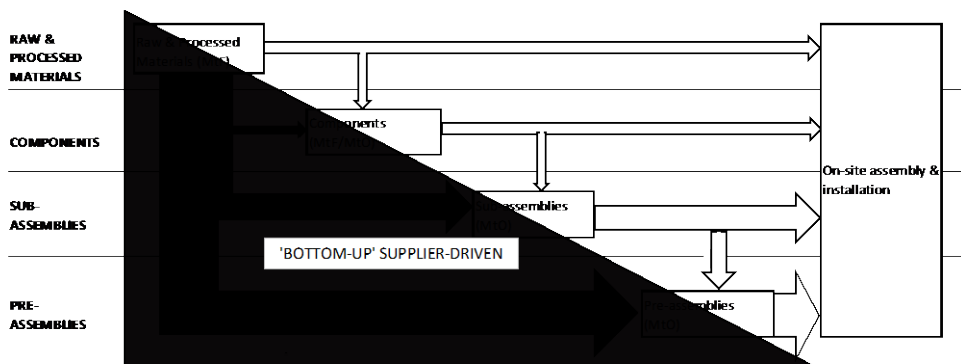


Figure 6.2 Material flows for bottom up supplier-driven construction (source: by author)

The three types of procurement are summarised in Figure 6.3 as modified versions of the Harper diagram.

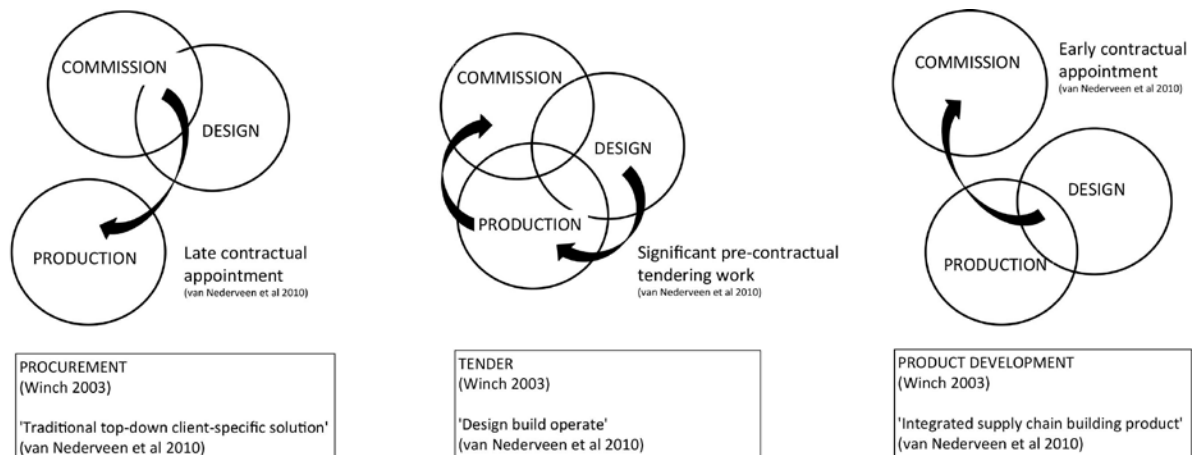


Figure 6.3 Process for procuring a building (source: by author based on models by Harper 1990; Winch 2003; van Nederveen et al 2010)

The model shows that in traditional procurement the production phase is separate from the commission and design phases as is shown in the diagram; the commissioning and design team develop a fully designed concept separately, which is delivered top-down to the production team. In a tender situation, the client, design team and production team negotiate a design and build solution and so these are shown interlinked. In a product development process using an integrated supply-chain the commission phase is separate to the design and production; the solution is developed by producer and designer together and then offered to the commissioning client.

The studies confirm a correlation between the extent of off-site and early supplier involvement. The research also verifies the link between a tendency by clients to commoditise their buildings using routine solutions, and an increased interest in supplier-driven made to order products. However, in the cases investigated, even where the supplier was providing significant elements of the building structure, the client still engaged in a design and build contract with a main contractor rather than a supplier-driven contract. The producer of the modules therefore became a sub-contractor to the main contractor and not a product supplier direct to the client.

This arrangement with suppliers suggests a more varied negotiation between commissioning client and producer as shown in Figure 6.4. The routine projects in these case studies do not use uniquely supplier-driven products, but a combination of supply-driven and client-led aspects. In the model outlined here the producer is offering a make to order (MtO) solution on elements that can be pre-designed through the mass customisation of a design to order (DtO) product, but there are still concept to order with make to concept (CtO/MtC) elements leading to a hybrid of customised and bespoke solutions.

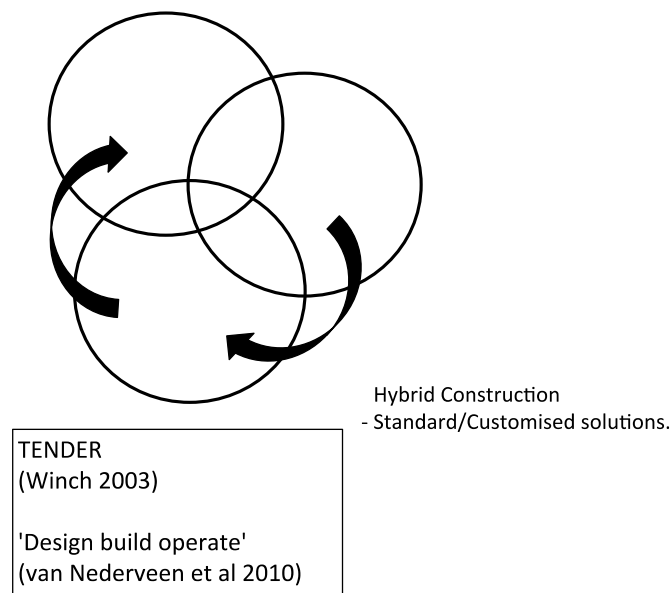


Figure 6.4 Balanced model negotiated between commission, design & production (source: by author based on Winch 2003 and van Nederveen et al 2010)

6.3.2 BUILDING DESIGN PROTOTYPING (WP 4)

The research combines design theory models for linear and non-linear processes (Pugh 1990; Cross 1990; Lawson 2004, 2006) employing phases of conjecture, analysis and synthesis to different degrees. These approaches respond to different degrees of brief definition (Cross

2001), addressing ill definition (Cross through framing (Schön 1983; Atkin 1992) and adaptation of co-evolutionary theories (Poon & Maher 1997) leading to varying trends in standard repeated, innovative and creative design solutions.

Figure 6.5 summarises Gero’s model. This time shows how it can be related to further theories from literature. Notably research by Dorst & Cross (2001) design roles and types of multidisciplinary design. As a first application of prototyping theory to building, this model continues to show increased relevance and links to other areas of research.

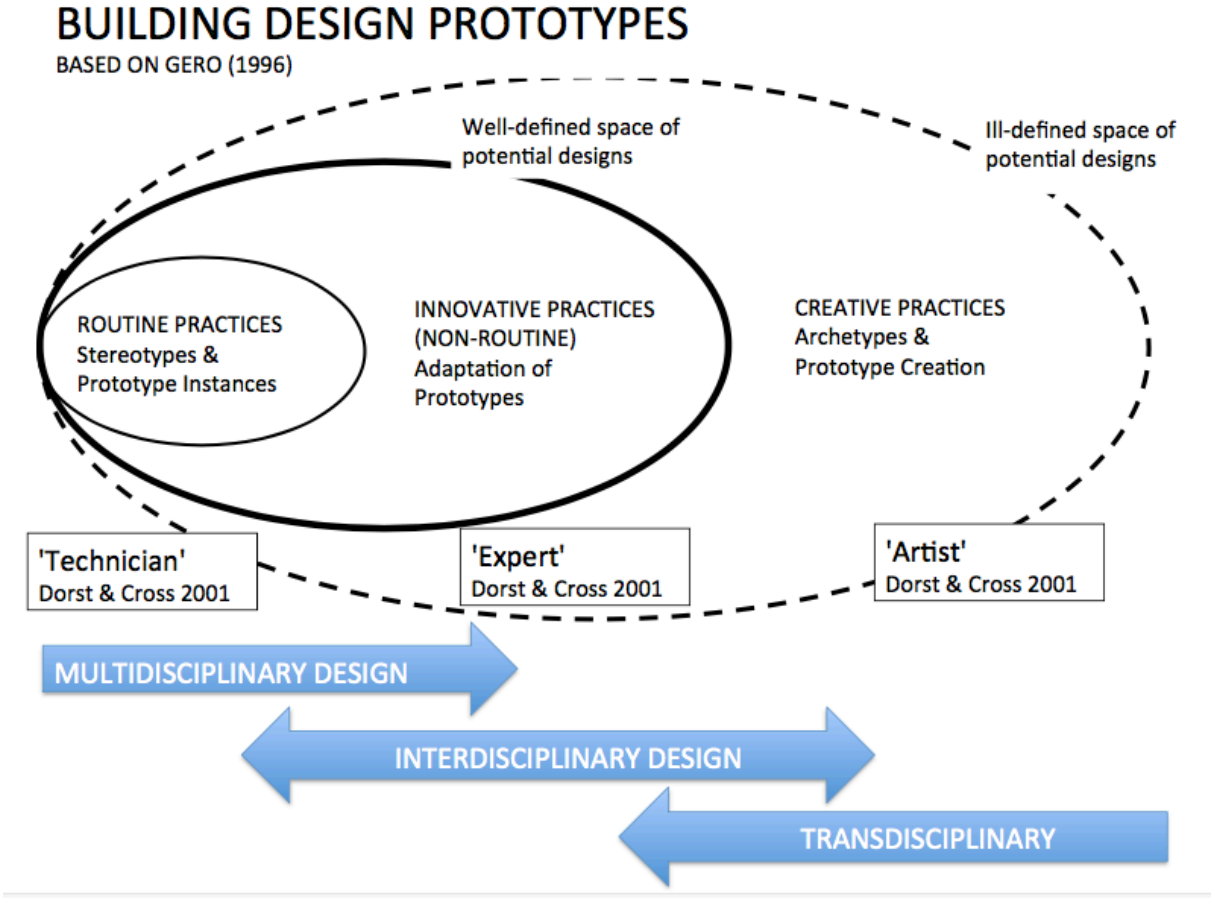


Figure 6.5 Practices, prototypes and design roles (source: author based on Gero 1996; Dorst & Cross 2001)

6.4 CONTRIBUTIONS TO PRACTICE

Construction is an important sector for the UK economy and national economies worldwide; the research is set by the context of UK government policy initiatives (Latham 1984; Egan 1988; Wolstenholme et al 2009; Cabinet Office 2011) to improve efficiencies in the construction industry and these studies aim to address some of the imbalance of client needs with initiatives to increase levels of industrialisation, particularly for off-site manufacturing.

6.4.1 ISBU MODULAR PRODUCT DEVELOPMENT (WP 1-3)

So the implications for practice are to improve understanding applications of off-site construction and the ISBU modular unit as well as use of digital tools. The use of dry-freight shipping containers as ISBU modules has been a disruptive move within the construction industry to propose an alternative system for modular construction. The units are highly standardised and from a mature manufacturing base, and therefore offer an alternative option. Digital tools, use of BIM to augment and rationalise the design information, aid repetition and adaptation of component-led approaches such as kit-of-parts.

ISBU construction does not suit every project, but in a situation where the client is willing to tender the project through a set of employer's requirements that allows the contractor to develop a proposal with a supplier, there is more opportunity for a design to order and make to order scenario for a mass-customised version of the ISBU pre-designed product. When this occurs, the design teams can focus more effort on realising that streamlined design and production process.

6.4.2 BUILDING DESIGN PROTOTYPING (WP 4)

Gero's prototype model offers a good representation of the stages encountered in the case study. The prototype generation stage where new structures and variables are being created (either from existing prototypes or completely new concepts) matches the description offered by the interviewees of how the platform, concourse and canopy roof designs emerged.

Designers are not always aware of the types and methods of design being undertaken, but as the building design prototype model shows there are differences in approach for routine, innovative and creative problem solving. The fact that the model can be used to formalise the movement from a more time-consuming creative activity to innovative or routine solutions makes it a useful tool for design practice. By defining prototypes, and by identifying the unique elements of the design, such as site-specific factors, repeat or similar designs might become more widespread. Given also that a prototype design can be informed by constructability issues such as off-site methods, repeated solutions through product prototyping (Ulrich & Eppinger 2008) could lead to construction improvements as well.

6.5 CRITICAL EVALUATION OF RESEARCH

Modular construction using ISBUs is a little-known area of research and any academic research on this topic is useful. Perhaps a more important question to pose is whether ISBU modular construction is relevant to the industry since it represents a very small part of the off-site market. As modular construction units they are more suited to temporary use because of their inherent capacity for re-use.

The product prototyping process (Ulrich & Eppinger 2008) of development through successive initial construction products matches accounts for previously successful product development cases from literature. However, the detailed process to prototype the module was fairly unique, due to the specific circumstances of the pre-existing configured product and was really an adaptation of an existing product, although dimensionally it was quite different. The engineering team's attempt at fine-tuning the structure of the units was not successful due to the fairly standard specification that was already in place for the dry-freight container. In any case, product refinement was not a major priority for the manufacturer.

Nevertheless, for temporary dwellings the engineering performance data will continue to be useful. There are many unused shipping containers globally, so they are likely to feature in future buildings. Future research should therefore be focused on optimising temporary structures using ISBU modules. Research could include improvements in re-use of materials, better connection designs and different standard configurations of units for temporary buildings.

With respect to production and procurement strategies, the case study numbers involved in this research are too low for the findings to be reliably generalised. The reluctance of clients to engage in direct supplier contracts needs to be further researched with other case studies and this could be a topic for further research.

The dilemma faced by the ISBU manufacturers in deciding whether to develop and market their standardised or a bespoke product is similar to the choices being made by other product manufactures in construction. The decision to standardise suggests again that temporary

modules, which are arguably more likely to be standard due to lesser planning restrictions, are a better option for ISBU construction.

The research work on prototype theory is preliminary but develops a model that can be applied and tested through future research projects. There have been few applications for this theory outside its original field of artificial intelligence (AI) research, which makes it a promising line of enquiry for future development. Future research could involve projects to further test out the viability of the different prototyping practices and disciplinary activities outlined in this thesis.

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APPENDIX A CUSTOMISED CONTAINER ARCHITECTURE (PAPER 1)

Full Reference

Robinson, A.C., Swindells, T., (2012). Customised Container Architecture. Proceedings of the American Collegiate Society of Architects 2012 Fall Conference & Modular Building Institute Regional Institute Meeting. Offsite Theory & Practice of Architectural Production, September 27th - 29th, Philadelphia, Pennsylvania, USA.

Abstract

Large-scale urbanization with transitory populations requires buildings with adaptability; buildings that can be designed, commissioned, and assembled, and then later disassembled using similarly efficient methods. With the emergence of Building Information Modelling (BIM) and Computer Aided Manufacture (CAM) this has opened the possibility of a more agile, customised building product optimized through prototyping, and an integrated design approach for assembly and operation. By using the ISO intermodal container platform, with its universal components and mature manufacturing base, the building product becomes an internationally deployable modular volumetric building with factory finishes, well insulated and air-tight spaces, and capable of use in low to high-rise construction. The research draws on precedents, recent project case studies and virtual and physical prototypes to measure the effectiveness of BIM on analysis, detailing and manufacture. The use of container technology offers a unique case-study of interdisciplinary innovation and product development transferred directly from manufacturing into construction.

Keywords

Shipping Containers, Customisation, Manufacturing, Product Development

Paper type

Conference Proceedings

1 INTRODUCTION

The use of shipping containers as building units has been widely reported, including 2008 ACSA Proceedings [35]. The re-use of existing containers in buildings solves simultaneously the environmental issues of steel container waste and reduced embodied energy for construction materials.

An alternative approach for container buildings is to use new, purpose-made manufactured units. These units are based on the ISO standard container platform but fabricated to better suit typical room sizes. While not waste-saving in the same way as buildings made from re-used units, the units are self-contained, with simple robust connections, which are easy to disassemble.

Project cases at Buro Happold consulting engineers have combined knowledge from a series of projects: Container City in 2001 by Urban Space Management, followed by the Travelodge & Premier Inn hotels from 2003 – 2009 with Verbus, the Nomadic Museum in 2005 by Shigeru Ban, the pan-European Hotel product in 2006 by KKA Architects, ‘MySpace Pod’ by Will Alsop in 2008, and more recently, the temporary event hotel product for ‘SnoozeBox’ in 2011 - 2012.

This paper is written in three parts; using case studies it charts some key architectural, technical and product development issues of containerized buildings. Part I - Container Architecture, describes the history of freight transport, leading to the large-scale availability of redundant containers, the social and economic factors for containerized buildings. Part II - Container Technology, describes standard unit configurations and the European technical certification and code requirements for steel modular units. Part III - Product Design and Parametric Digital Architecture, discusses issues of prototyping, standardization, customization and platform design. It also looks at recent models for scalable building designs that optimize geometric components, quantities, cost data and carbon footprint.

2 PART I – CONTAINER ARCHITECTURE

2.1 INTERMODAL FREIGHT TRANSPORT

The shipping and railway industries used “intermodal” container boxes to transport furniture from France to England as early as the 1890’s, over 50 years before the modern intermodal container with its characteristic twist locks emerged in 1956. [21].

The container is the central product of an automated system used to deliver goods anywhere in the world with minimal costs and complications. Such is the imbalance of trade between producers and consumers that it is less expensive to abandon containers at the point of delivery rather than transport them back empty. Added to this have been global fluctuations in world trade and shifting preferences in sizes of containers for shipping [21], which has resulted in a surplus of steel units in many ports. The Dry Freight container is the most common, and in 2005 it was estimated that there were at least 125,000 units in the UK and 700,000 empty units in US ports alone [23] [19].

2.2 CONTAINER BUILDINGS

Architects had observed that stacked units in ports look like neighbourhoods and provide a type of ready-made construction system [19]. Redundant reclaimed containers, also called ‘deadheads’ [4], have been adapted and assembled with other more conventional building elements to create low cost, low carbon footprint buildings. Although there is no shortage of containers for re-use, their take-up for construction has been relatively small. With the units’ external appearance left exposed they present an uncompromising aesthetic: a kind of ‘cosmopolitan building block’ [19], and the standard dimensions of a container, determined by shipping and transport requirements, do not immediately suit habitation use. This has led to some novel applications and configurations of units [19]. Fortunately the standard container has a robustness and rigidity that suits modification.

2.3 SOCIAL AND ECONOMIC FACTORS FOR CONTAINERIZED BUILDINGS

Kotnik describes the cultural development of the container building as ‘bottom-up’ [19]; containers were first used as shacks and shelters in low economy countries before they became popular with architects. Containers have been successfully deployed in areas prone to extreme environmental conditions [23] and used as emergency shelters and medical centers such for post-hurricane housing [6] [11].

Container buildings are cheaper than most modular building systems, which in Europe can be anything from 5 to 20% more costly [24] than traditional on-site construction. Modular buildings bring other commercial benefits to a project such as program savings, more predictable quality, and reduced snagging, but other factors may come into play in the choice of modular units, such as issues of access, and local availability of skilled labor.

Case Study 1 – Uxbridge Travelodge

The Uxbridge Travelodge is an eight-storey hotel building completed in 2006. The site was located adjacent to a 24-hour bus terminus. All site deliveries including the container modules had to be delivered across the main access road, and at no time could a bus be delayed by more than 10 minutes during site deliveries. Due to its layout, the building required additional steel framing and some non-standard units. The building took 16 months to complete. It was clad in traditional brickwork.

Large hotel operators who are ‘repeat-order’ clients [9] [30] may be looking for a module supplier who can bring long-term value, maintain a consistent output, and develop strong commercial relationships with their framework contractors.

Some permanent building types: student accommodation and budget hotels have a shorter life-cycle than commercial and residential buildings. Contributing factors include unplanned urban expansion, extreme climate events, and transitory worker populations. This has led to some clients taking a greater interest in building adaptation and the possibility for demountability and relocation; qualities offered by containers.

Case Study 2 – Tempo Housing.

The largest container development in the world is 1000 re-used units for a student housing development at Keetwonen, near Amsterdam, Denmark, which was fully completed in 2006 (www.tempohousing.com 2010). The housing is temporary and designed to be dismantled. The extended lease ends in 2016. Tempo housing have also built other residences including a re-locatable five storey worker housing development in Holland, due for relocation in 2013.

These buildings have characteristics closer to manufactured products. The buildings are ‘semi-permanent’ and the characteristics of a commodity, a measured depreciation and a quantifiable end-use value. Due to the projected rise in energy costs, re-use is likely to become a more significant factor in the future choice of building systems.

3 PART II – CONTAINER TECHNOLOGY

3.1 INTERMODAL STEEL BUILDING UNITS (ISBUS)

Intermodal Steel Building Units or “ISBUs” are re-used containers converted for building use. Units are commonly 8ft (2.4m) wide and 20 or 40 ft. (6.1 or 12.2 m) long. There are also ‘High Cube’ that are 48 to 53 ft. (14.8 to 16.3 m) long. These types of modules have been used in low-rise construction, and modified to suit normal room sizes by joining units together, with partial removal of side panels. Unit arrangements are sometimes combined with other structures such as open-plan steel frames.

Case Study 3 - Container City, Urban Space Management

Contractor Urban Space Management developed the residential and office building ‘Container City’, in 2001 (www.containercity.com 2010) the first major UK project to re-use containers, and it was completed in just five months. The containers are left exposed with a ‘Lego’-like aesthetic [4]. The success of the first container city project led to a further floor of units being added to the original building and another separate building being added on the same site in 2002 [35]. Urban Space Management followed this project with a college building and a sports hall in collaboration with Architects Scabal [4].

The alternative form of container buildings constructed using purpose-made units are closed-cell, factory finished, volumetric units, varying from 8 to 14 ft. (2.4 to 4.3 m) in width and 20 to 53 ft. (6.1 to 16.3m) in length. They are stacked to form multi-storey structures. As with other volumetric construction systems they have the advantage of being built and fitted out under factory conditions, but made with the universal ISO components.

Where the container is enclosed in external cladding, insulation is placed outside the container. Further insulation may be used inside the container for acoustic isolation and fire protection. The container is a warm frame and its watertight steel shell can be used as its vapour barrier.

Case Study 4 – Verbus System

The Verbus System, a collaboration between contractors George & Harding and Buro Happold, have built seven Travelodge and Premier Inn hotels in the UK between 2003 and 2009. The commercially manufactured modular building units are made and fitted-out at the CIMC factory in Guangdong Province, China.

These oversized units with bolted and corner connections, are shipped to Europe on a standard container ship and transported to site on standard container transport vehicles. The units are fabricated in batches of around 75 to 150 units and take one week to fabricate and two further weeks to fit-out. The CIMC factory at Shenzhen is normally fabricate up to 2000 standard dry container units per week.

The requirement for non-standard containers has been intermittent, typically every 6 months. The module production line benefits from being part of mature and much larger manufacturing plant. This has meant it can more easily respond to the stop-start demand for container buildings.

The hotel buildings are two to eight stories high with floor areas varying between 25,000 ft² and 74,000 ft². Despite the distances involved, the overall production cost of shipping container units is comparable to traditional construction. This is due to the low cost of materials and labor in East Asia and the very low cost of container transport.

3.2 TECHNICAL PERFORMANCE & DETAILING

Compared to most building systems, container architecture is very recent [21] [19]. The design and detailing of new construction systems often emerges from existing building typologies [14], and containerized construction shares some of its detailing with existing systems, but some of its detailing is completely original.

For prefabricated units to be certified in Europe: ‘CE marked’, the performance characteristics are described in the Guidelines for European Technical Approval [15]. Among the ‘Essential Requirements’ in ETAG 023 there are at least four key characteristics for containers: ER1 - Mechanical resistance and stability, ER2 - Safety in case of fire, ER5 - Protection against noise, and ER6 - Energy economy & heat retention [15].

3.3 ER 1 - MECHANICAL RESISTANCE AND STABILITY

The requirements are for safe transmission of vertical and horizontal loads, and prevention of collapse. In containerized construction, vertical load is transferred directly through the corner columns, which are restrained laterally against buckling by the steel infill panels. Horizontal loads are transferred through the sidewalls of the containers for buildings up to 11 stories or for higher buildings through a combination of braced steel cores and the container walls. Like many cellular buildings, containerized buildings use frames to transfer support loads from the modules to more open plan areas. In the event of collapse of the module or its support, containers are linked horizontally, so that adjacent units can carry their weight. A similar approach is used for other volumetric building systems (Gorgolewski et al 2001).

3.4 ER 2 - SAFETY IN CASE OF FIRE

Fire resistance, the statutory time that a structure that although weakened, still remains stable after a fire has taken hold, is defined through code requirements. An alternative method is achieved by calculating a temperature-time response of materials with a calculated fire load using a thermal model. The complex interaction of material strengths, stiffness and load paths can be evaluated by design calculation and finite element thermal modeling, leading to the estimation of a reduced strength for a given time period [36].

Case Study 5 – Hull Premier Inn

The Premier Inn owned hotel in Hull is the tallest structure in Europe to include containers as part of its permanent load bearing structure. A 6-storey modular structure sits above seven-storey car park and hotel reception. The regulatory 2-hour fire performance was re-negotiated with building control inspectors through a ‘fire engineering’ approach permissible under UK regulations. A predicted fire load with fire evacuation strategy combined with an analysis of steel temperature gains on the steel in the containers led to a 50% saving on fire boarding protection in the units.

3.5 ER 5 - PROTECTION AGAINST NOISE

Buildings are susceptible to high levels of external noise and problems with internal noise transmission. Airborne sound tests measure the reduction in noise through walls and floors for sounds at a number of different frequencies with a standard reverberation (decay) time, and adjusted using a sound reference curve to establish a single minimum figure at 500 Hz which is a frequency level corresponding most appropriately to human hearing. Impact sound tests measure the sound level in a room below a floor that is subjected to a standard impact source. Direct sound transmission occurs through a separating structure, but there is also flanking transmission through building elements adjacent to the separating structure being measured.

Acoustic Criteria	Measured on-site noise levels
UK Building Regulations Part E	DnTw + Ctr
Airborne Noise: Separating Walls	> 50 dB (min value 43 dB)
Airborne Noise: Separating Floors	> 54 dB (min value 45 dB)
Impact Noise: Separating floors	< 55 dB (max value 62 dB)

Figure 1 Site Measured Noise and Impact Reductions through separating walls and floors

Figure 1 shows the noise performance on recent container buildings. Containerized construction benefits from isolation, materials layers and cavities similar to other volumetric systems, but its greater mass also means that it can match the performance of more massive construction.

Case Study 6 - Heathrow Travelodge.

Completed in 2007, this hotel was built directly under the flight path of the second runway at this major international airport. Peak external noise levels above the building were measured to be 100+ dB. The building modules and external envelope accommodated triple glazing and additional acoustic insulation layers. The roof was covered with a concrete slab for further sound reduction. This was supported off the units without additional strengthening.

3.6 ER 6 - THERMAL PERFORMANCE

Thermal performance of building systems is calculated for the conservation of fuel and power. Under UK national regulations, aspects will include not just the fabric performance, but also mechanical and electrical systems and the regulations specify minimum requirements.

In containerized construction there are two different basic build-ups of insulation materials. In containers where the external surface of the container is left exposed, the walls are effectively a cold frame, and insulation layers have to be built up inside the container, including a vapour barrier on the warm side of the insulation. This becomes problematic when the external shell of the container passes through an envelope to become an internal wall and has to be insulated. Often circulation spaces outside containers are not totally enclosed in order to avoid this issue.

Case Study 7 – MySpace Pod, Will Alsop

MySpace Pod is a prototype student pod with a similar configuration to Tempo Housing with exposed container walls. A significant design challenge with these types of structures is to establish a continuous thermal barrier in order to avoid a cold-bridge forming where the external surface of the container enters the interior, which would otherwise result in significant heat loss and internal condensation.

4 PART III – PRODUCT DESIGN & PARAMETRIC DIGITAL ARCHITECTURE

Freight containers come from a customizable product family of modular elements [27] with interchangeable sub-assemblies and component groupings to an ISO standard configuration. Containers are described as having a platform architecture; a platform being a collection of assets with component designs that are shared by multiple products [34]. As a product family on a common platform, these containers meet a variety of market needs [31].

4.1 CUSTOMISATION AND PLATFORM DESIGN APPLIED TO BUILDINGS

Container buildings use the platform concept for the container units and building designs. In this standard building configuration, a platform architecture approach is being used at two

different levels: the ISO standard platform for the containers, and the whole building platform made up of varied configurations of modular building elements.

ISBUs use pre-assembled components of the container such as the rails, walls and corner fittings that create a volumetric box, and it is then further modified for building use, with insulation, linings and internal fittings and finishes added to suit the required internal environment [29].

The units are assembled into the whole building, where the final shape of the building is determined by the arrangement of modules, in response to the overall building site plan, the client brief and the financial model for the number of habitable spaces that need to be provided. In product design terms this is similar to a configurational product family design where a platform is made up from a number of modules that can be added or removed to generate variety [32] [33].

The development of purpose made building units based on a container platform can be described as a top-down approach in product development terms [32] because of the deliberate decision to use an existing universal platform. Similarly, the re-use of containers is a ‘bottom-up’ process [32] that has emerged and developed through trial and error followed by a rationalization of the design.

4.2 BUILDING INFORMATION MODELING & PARAMETRIC DESIGNS

A further development of the customized container product has been the development of a standard building configuration for hotels and other residential buildings, based on a ‘complete building’ platform with customizable architecture with clear advantages for a parametric approach to building modeling and production.

Case Study 8 – Pan European Hotel Product

Buro Happold collaborated on a ‘pan-European’ branded building product with KKA architects based around an optimized configuration of the Verbus System components. The client for the hotels was a budget airline company serving multiple flight destinations at smaller out-of-town airports in Europe. The airline recognized that their flight patterns could change over time, and were therefore interested in a more easily demountable hotel building. The product was designed to an advanced stage with full prototypes manufactured in China and shipped to the UK. However, the project was not taken beyond the prototype stage.

4.3 PARAMETRIC DESIGNS

Building Information Models (BIM) are used to generate and manipulate building information using 3D parametric data for geometric components and their layouts, allowing building information to be generated automatically. BIM works by using data with object orientated representations that can be extracted and manipulated to show the best building arrangements and therefore improve the decision-making process [2].

ISBUs with their container platform lend themselves very well to a design using parametric models. This is in effect a scalable approach to platform design [37], with some constant

variables and others scaled in one or two directions, to generate variable forms within the same product family.

Case Study 9 – SnoozeBox Event Hotel

A self-contained flexible hotel product adapted from single-use standard shipping containers. The building can be set up in 48 hours. The system uses proprietary products and standard container components, as well as some purpose-designed elements, such as the off-grid plant services and collapsible external circulation stairs and balconies.

Parametric models have become increasingly sophisticated, having Building Object Behaviours (BOB) with domain expertise embedded into arrangement of elements [16] [38]. This approach has parallels to agile product development practices [1] where economies in variety, cost control and production are achieved in mass customization of a standard product by actively quantifying the costs of variety of solutions during the different stages of the design and production processes, and comparing this data with their design flexibility for modularization and customization.

During the design process, parametric data can be used to assess costs based on element sizes, materials and location. These values can be further refined by considering subjective factors such as commercial competition and quality [12]. An additional dimension to optimization of parametric design and cost data is the use of carbon data to determine building carbon footprint [38]. The combined data for cost and carbon can be assessed iteratively through feedback loops in order to reach optimized solutions.

5 CONCLUSIONS

The container is multi-dimensional design solution meeting technical requirements for building use that is predicated by the adaption of a pre-existing industrialized product. Containerized buildings have a hybrid construction typology based on a combination of standard container frameworks, volumetric building technologies and more conventional building construction techniques.

Only re-used containers offer the advantages reduced carbon footprint, but newly manufactured units are robust, highly adaptable and easily transported. The purpose-made units benefit from a product family architecture based on an ‘open’ existing platform design, produced in a mature manufacturing environment. Its ease of transportation combined with low manufacturing costs makes it a viable commercial alternative to many modular and traditional systems.

6 NOTES

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APPENDIX B EMBODIED CARBON OF SHIPPING CONTAINER ARCHITECTURE BASED ON AN ISO STANDARD PLATFORM (PAPER 2)

Full Reference

Robinson, A.C., Wedge, J. Sauven, E., Swindells, A., Gibb, A.G.F., Austin, S.A., (2012). Embodied Carbon of Shipping Container Architecture based on an ISO Standard Platform. Proceedings of the Creative Construction Conference 2012, June 30th – July 3rd, Budapest, Hungary.

Abstract

Shipping containers come from a customizable product family of modular elements with interchangeable sub-assemblies and component groupings to an ISO standard configuration. In their intermodal transportation use, these modular assemblies are volume produced to provide a selection of self-contained closed and open units. Compared to most building systems, container architecture is very recent. Containers offer an idealized model for customizable modular architecture. They have a standard universal platform, and they can be arranged in standard building configurations. Given the recent advances in the use of parametric model databases for building information modeling (BIM) and computer aided design (CAD) & manufacture, this research takes advantage of the benefits and uptake of scalable building designs, costing tools and carbon measuring in containerised buildings. In this first stage of research, comparisons are made between the carbon footprint of new fitted out modules shipped to Europe from East Asia, compared to similar but re-used, locally sourced containers, and non-container type modules also manufactured locally. The ISO units provide a uniform, transferable architecture, but as a result of their standardised universal platform structure, containers are heavier and less efficient to use than competing modular systems, and there are drawbacks with carbon footprint compared to locally sourced material options. In later stages, the parametric model will be used to optimize other factors for containerised buildings and compare with other building types.

Keywords

Design, Containerisation, Parametrics, Modularisation, Low Carbon

Paper type

Conference Proceedings

1 INTRODUCTION

Containers offer an idealized model for customisable modular architecture. They have a standard universal platform, and they can be arranged in standard building configurations. Given the recent advances in the use of parametric model databases for building information modeling (BIM) and computer aided design (CAD) & manufacture, this research takes advantage of the benefits and uptake of scalable building designs, costing tools and carbon measuring for exploring containerised buildings and comparing them to other similar systems. The paper first looks at the product architecture of the shipping container and its recent adaptation to buildings in its different forms. The main focus in this stage of the research is to measure the carbon footprint of these building types compared to more standard modular systems. Later research stages will test the usefulness of a parametric model to optimize materials of containers compared with other building options.

2 INTERMODAL SHIPPING CONTAINERS

Standard shipping containers are stackable, transportable, robust, modular units; they are prefabricated, volume produced and reusable products. The term ‘intermodal’ denotes the use of multiple modes of transport (ISBU 2012). The container has had a major impact on industrialised society through the economies of transportation; it is a ubiquitous product, but also a ‘disruptive’ technology due to its effects on shipping and global manufacturing trends that had until recently been largely overlooked (Levinson 2006, ISBU 2012, Robinson et al 2011a).

3 MODULAR PRODUCT ARCHITECTURE

Shipping containers come from a customizable product family of modular elements (Pine 1993) with interchangeable sub-assemblies and component groupings to an ISO standard configuration. Containers can be described as having a platform architecture; a platform being a collection of assets with component designs that are shared by multiple products (Ulrich & Eppinger 2003). As a product family on a common platform, these containers meet a variety of market needs (Simpson 2003).

Product family design uses either a top-down or proactive approach where a family of products is developed based on a platform and its derivatives or a bottom-up approach with existing products redesigned to be more standardised (Simpson et al 2001; Syed 2010). The steady development of the modern container that started in 1956 largely came about through a bottom-up approach, but since ISO standardisation it can be argued that it has followed a largely top-down approach, by using a standard platform to create a family of products. This paper will further explore how containerized building designs have also followed these top-down and bottom-up approaches.

4 CONTAINERS AS BUILDING UNITS USING THE ISO STANDARD PLATFORM

Compared to most building systems, shipping container architecture is very recent. Since 2001 there has been a steady stream of imaginatively designed buildings using the container.

Sometimes referred to as ‘cosmopolitan building blocks’ (Kotnik 2008) with a ‘Lego’-like construction aesthetic of bold colours (Building Design 2009). See Figure 1.



Figure 1: Container buildings provide opportunities for unique architecture

When containers are used as ‘Intermodal Steel Building Units’ (ISBUs), they can take on the characteristics of an open building system (Groak 1992): being dimensionally standardised, with common connections, and therefore leading to the possibility of interchangeability between manufacturers. Using the container platform as a building unit leads to a common set of systems/subsystems, components and processes, which should create variety at lower cost (Simpson 2004).

There are two main forms of container construction: reclaimed re-used containers converted to ISBUs, and purpose made manufactured building units based on the shipping container platform. Both reused and new manufactured solutions benefit from the increased ability to be re-locatable (Kronenburg et al 2003, LOT-EK 2003, Robinson et al 2011a).

The platform concept for using containers as building units works along similar principles to the container product family. Pre-assembled components of the container such as the rails, walls and corner fittings that create a volumetric box are modified for building use, with insulation, linings and internal fittings and finishes added to suit the required internal environment (Robinson et al 2011b).

The units are assembled into the whole building, where the final shape of the building is determined by the arrangement of modules, in response to the overall building site plan, the client brief and the financial model for the number of habitable spaces that need to be provided. In product design terms this is similar to a configurational product family design where a platform is made up from a number of modules that can be added or removed to generate variety (Simpson 2003, Syed 2010).

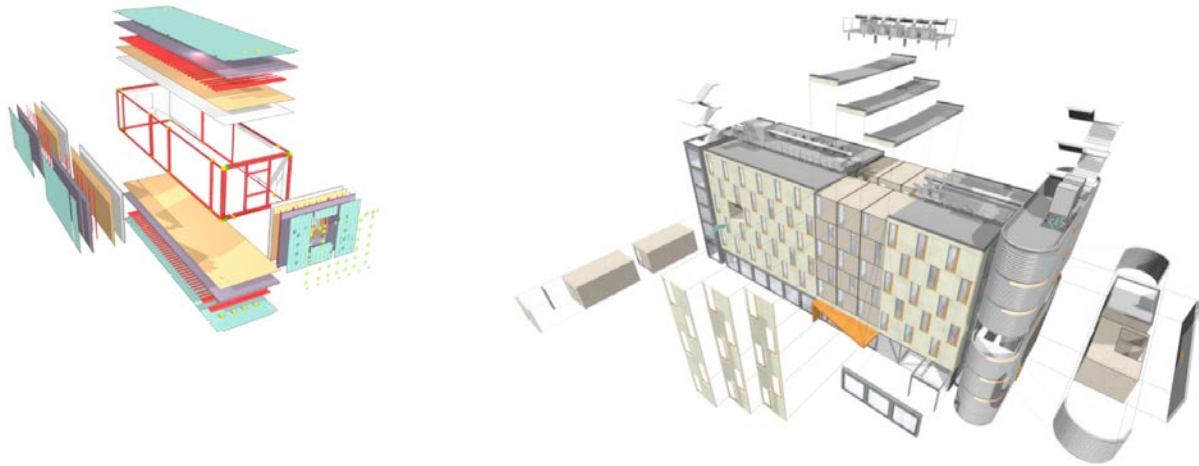


Figure 2: Module based on an ISO platform as a part of the whole modular building platform

A building construction platform design is therefore being used at two different levels: the ISO standard platform for the ISBUs, and the whole building platform made up of a varied configurations of modular building elements.

5 RE-USE OF REDUNDANT SHIPPING CONTAINERS

In 2005 it was estimated that there were 700,000 unused containers in US ports alone and 125,000 redundant containers in UK ports (Marshall 2009; Kotnik 2008). Redundant reclaimed containers, also called ‘deadheads’ (Building Design 2009), have been adapted and assembled with other more conventional building elements to create low cost, low carbon buildings. In construction product design and development terms, the re-use of containers is a ‘bottom-up’ process (Simpson et al 2001). Interestingly, others have also described the container movement in its cultural development as ‘bottom-up’ (Kotnik 2008); containers were first used as shacks and shelters in low economy countries before they became popular with architects.

6 PURPOSE MADE MODULAR BUILDING UNITS

Similar to other volumetric systems, commercially manufactured modular building units using the container platform have been fitted out in a factory in South East Asia and shipped to Europe to become volumetric elements in cellularised buildings. The module production line benefits from being part of mature and much larger manufacturing plant, which allows it to respond to the stop-start demand for container buildings.

Normally, modular buildings are as much as 15 to 20% (post publication note: full range is 5-20%) more costly (NAO 2005) than traditional construction, but they bring other commercial benefits to a project such as time saved, predictable quality, and reduced snagging. However, these benefits may only account for 10% of savings (NAO 2005) in capital cost and there are usually other drivers for adopting modular. Despite the distances involved, the overall cost of shipping container units appears comparable with traditional construction and is therefore less costly than most modular systems. This is due to the low cost of container transport, and materials and labour in Asia being more competitive compared to Europe. Typical applications are budget hotels (Building 2008, Robinson et al 2011a), student

accommodation, and worker housing (Tempo Housing 2010) and mining camps (3Twenty Solutions 2011). Most units may have an external building envelope made from traditionally built cladding and roof elements, some to hide the origins of their construction (Building 2008, Robinson et al 2011a).

The product development of purpose made building units based on a container platform is a top-down approach (Simpson et al 2001) because of the deliberate decision to use an existing universal platform. This decision drives the design process and final outcome.

7 BUILDING INFORMATION MODELLING USING PARAMETRIC DESIGNS

Building Information Models (BIM) are used to generate and manipulate building information using 3D parametric data for geometric components and their layouts, allowing building information to be generated automatically. BIM works by using data with object orientated representations that can be extracted and manipulated to show the best building arrangements and therefore improve the decision making process (AGCA 2006).

ISBUs with their container platform lend themselves very well to a design using parametric models. This is in effect a scalable approach to platform design (Meyner & Lehnerd 1997), with some constant variables and others scaled in one or two directions, to generate variable forms within the same product family.

Parametric models have become increasingly sophisticated; with Building Object Behaviours (BOB) with domain expertise embedded into arrangement of elements (Ghang et al 2005). These models can be used to assign not just geometrical data, but consider other performance data and characteristics including costings. New integrated decision-making tools are being considered by the industry to assess and optimize options that consider the full performance of the building as well as its structure. These tools require a holistic approach with systems level thinking that accurately represent the complex behaviour and use of buildings (Bank et al 2011).

This approach has parallels to agile product development practices (Anderson 1996) where economies in variety, cost control and production are achieved in mass customisation of a standard product by actively quantifying the costs of variety of solutions during the different stages of the design and production processes, and comparing this data with their design flexibility for modularisation and customisation.

During the design process, parametric data can be used to assess costs based on element sizes, materials and location. These values can be further refined by considering subjective factors such as commercial competition and quality (Daschbach 1988). An additional dimension to optimisation of parametric design and cost data is the use of carbon data to determine building carbon footprint (Bank et al 2011). The combined data for cost and carbon could be assessed iteratively through feedback loops in order to reach optimized solutions.

8 CARBON INVENTORY LIFE CYCLE ASSESSMENT TOOL

The carbon inventory is a 'streamlined' Life Cycle Assessment (LCA) tool, using carbon as a single indicator rather than looking at whole life carbon measurement. A low carbon footprint does not automatically mean low environmental impact, which is measured using a collection

of indicators in addition to carbon footprint, such as environmental pollution, fossil fuel depletion and waste disposal (BRE Green Guide).

In most European countries, embodied carbon emissions are outside policy and planning guidance, but future EU standards are expected to elaborate on ISO 14040 with compulsory 'Environmental Product Declarations' (EPD) for manufacturers (CEN/TC 350).

This assessment follows guidelines in EN ISO 14040 to define assumptions, but there is little regulation nor consensus on standard procedures concerning this process. These assessments have been based on carbon data from Bath ICE Inventory v2.0 and the calculations use average national rates for transportation. The main purpose of this carbon inventory is to make comparisons between different building options, not to give accurate carbon emissions. Using average carbon emission rates, results are estimated to have an accuracy of up to +/- 25%.

For embodied energy reductions to have relevance, they need to be significant compared to overall energy needs of the building during its lifetime. Typically values of embodied energy in materials and their construction are typically 15% of overall energy use at current emission rates, but operational emissions are predicted to fall to 90% of current rates over the next 30 years (DEFRA 2010).

9 CARBON MEASURING AND COMPARISON RESULTS

The carbon life cycle analysis model has been used to measure the carbon footprint for a hotel building in northern Europe, comparing different scenarios. In all cases the building consists of 5 stories of room/corridor/room units and stair units as shown in Figure 3.

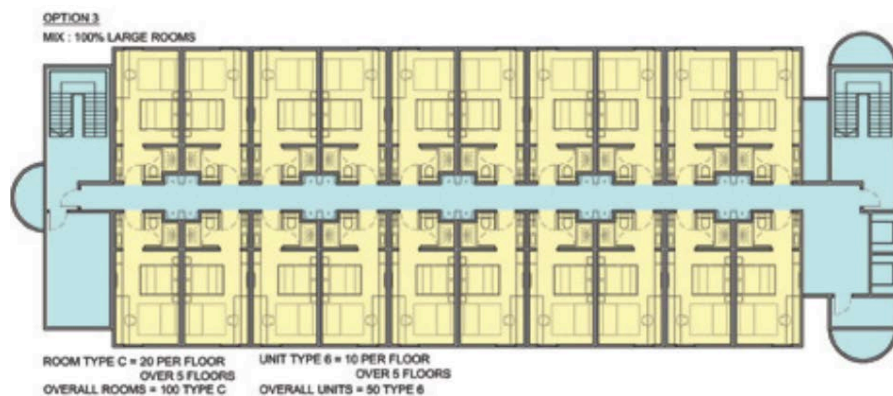


Figure 3: Typical Building Plan, 5 Stories, Total Floor Area 3075 m2

The analysis first looks at the container platform based modules fabricated and fitted out in South East Asia, transported by ship to UK and then by road transport to site. Foundations, ground works and external envelope are conventionally sourced in Europe and transported by road. The carbon footprint for the modules has been broken down in to constituent elements: steel shell, plywood and plasterboard walls, floors and ceilings, fittings. Only the mechanical and electrical services have been excluded. The embodied energy has then been calculated for the steel units, fit out, façade envelope and site works.

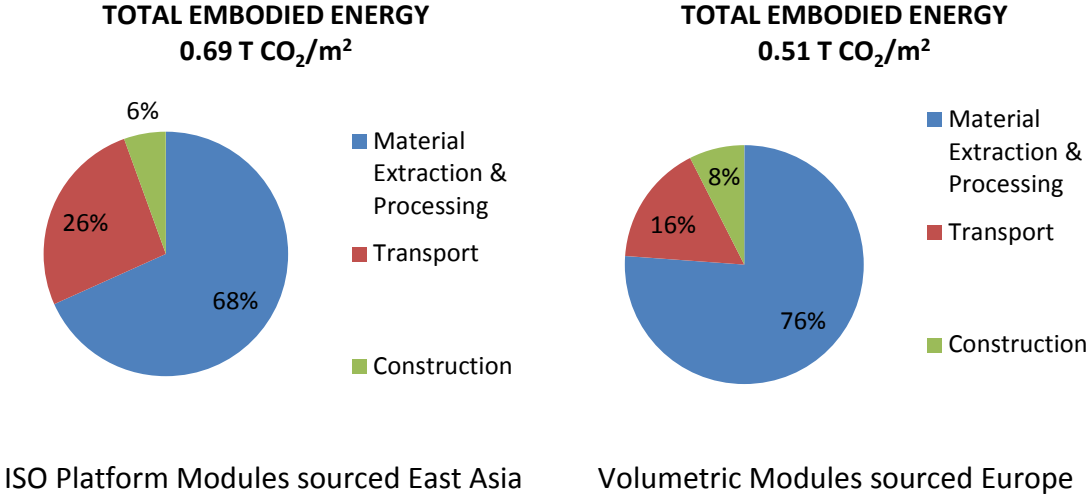


Figure 4: Embodied Energy Breakdown for hotel building using ISO standard platform modules

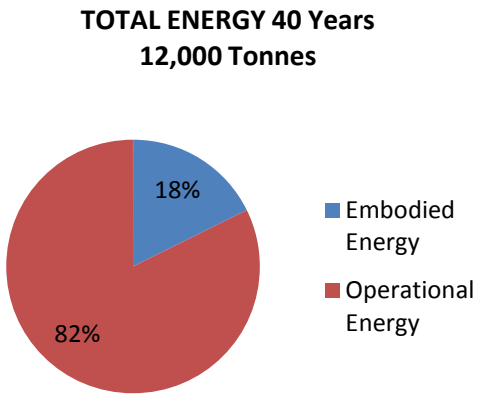


Figure 4 compares embodied energy for ISO standard modules from East Asia compared to nationally non-container sourced modules in Europe. There is a 20% increase in carbon due to transportation, and an 8% increase in materials when using the hot-rolled steel ISO container instead of a lighter cold-rolled steel frame normally adopted in Europe. Figure 5 shows the embodied energy for the containers as an 18% proportion of total carbon emissions for the hotel building being operated for 40 years (Carbon Emission Source: ICE 2.0 DEFRA 2010)

Figure 5: Total Carbon emissions for construction and operation of hotel.

Two further two options were measured and analysed to compare these modular buildings with a similar arrangement, but with re-used containers, and an equivalent steel frame building using more traditional on-site forms of construction with non load-bearing partition walls.

Figure 6 shows a breakdown of the carbon footprint for the substructures & site works, façade envelope, fit out and steel structure for all four options.

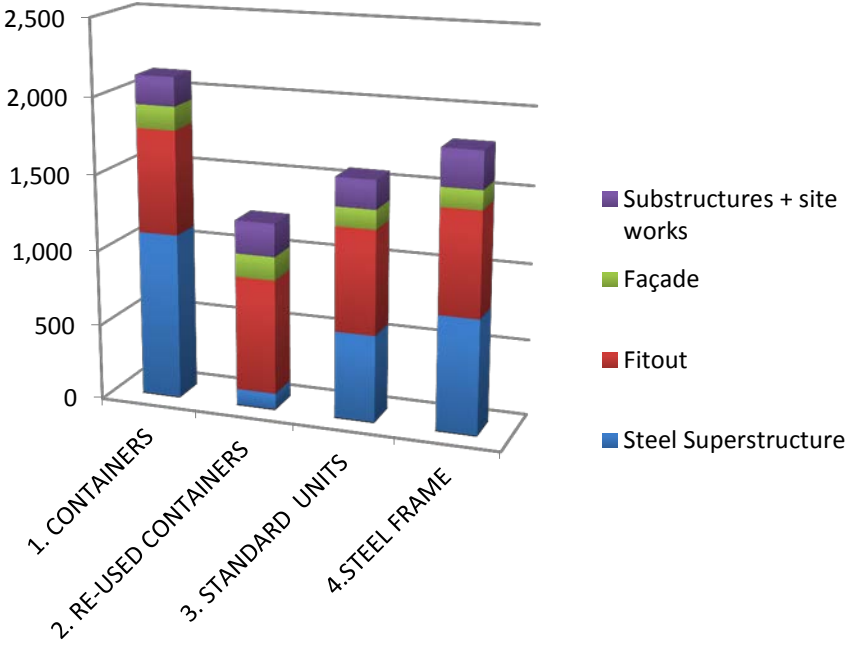


Figure 6: Carbon Footprint in Tonnes of carbon for different building options

The buildings made from recycled containers, assuming a zero-carbon footprint in their re-use in construction, have a 21% lower embodied energy (0.40 tCO2/m2) compared to the benchmark European sourced modules. Embodied energy for the steel frame building is 0.59 t tCO2/m2.

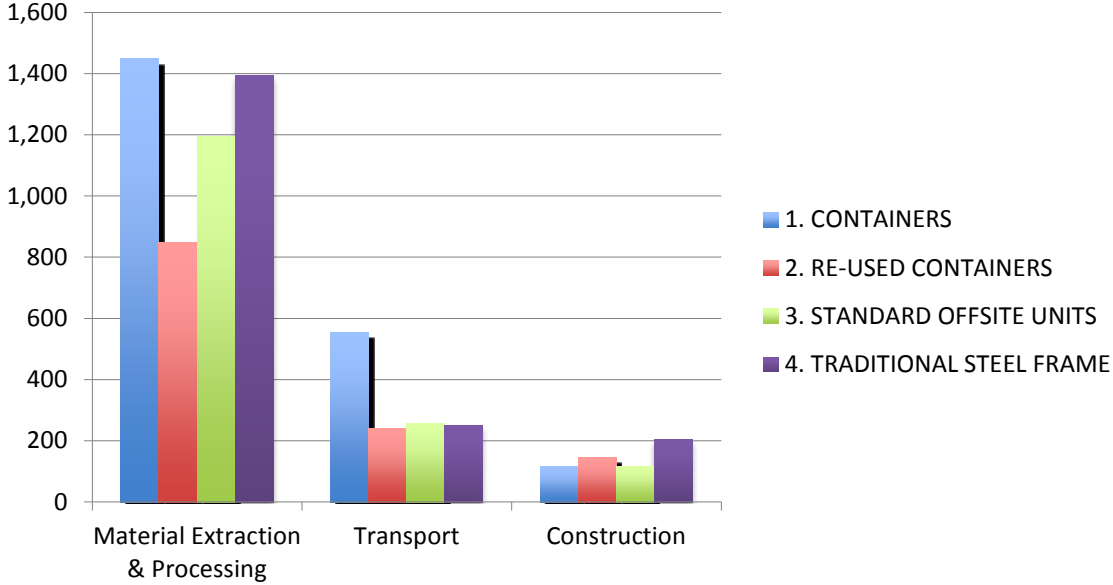


Figure 7: Comparative breakdown of embodied carbon tonnage for hotel building options

As shows in Figure 7, a breakdown of carbon in terms of materials extraction and processing, transport and construction shows that the embodied energy from ‘cradle to the factory gate’ accounts for over two-thirds of all carbon. This is understandable given that the main aim of modular construction is to minimize resources and energy use on site to a minimum, in the

belief that these can be more easily minimized within the more controlled environment of the factory.

Relative to the benchmark units, the modules based on the container platform have a 16% higher carbon footprint in their initial materials and processing. This is mostly attributed to their heavier construction of the modules using the container platform. In steel tonnage terms, the weight of the hot-rolled steel container units are over 1.5 times as heavy as the benchmark units which in this case are made from lighter cold-rolled steel, stiffened with plasterboard.

10 CONCLUSIONS

Purpose made manufactured building units using the container platform provide a uniform, transferable architecture. However as a result of their standardised universal platform structure, containers are less efficient in use of materials compared to modular systems. Their economic viability lies in the ability to be transportable as large-scale building element from another continent with lower materials and labour rates. Containers continue to be a disruptive technology for construction, where markets are normally driven by the domestic value of products and construction services. As with international trade, there are drawbacks with carbon footprint compared to locally sourced material options, although the re-use of existing containers is a good compromise while these continue to be available.

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APPENDIX C EFFICIENCIES IN DESIGN AND MANUFACTURING FOR CONSTRUCTION USING SHIPPING CONTAINERS (PAPER 3)

Full Reference

Robinson, A.C., Gibb, A.G.F., Austin, S.A., (2011). Efficiencies in design and manufacturing for construction using shipping containers. Proceedings of the 27th Annual ARCOM Conference, 2011, June 5th – 7th, Bristol, UK.

Abstract

Shipping containers are standardised, mass manufactured re-usable products with a structural typology that lends itself to applications in construction. They can be used as ‘offsite’ volumetric units for cellular accommodation, modular buildings and combined with conventional framed structures for open plan spaces. Taking findings from literature on manufacture for construction and containers, product design data, and semi-structured interviews, the use of containers has been studied to explore efficiencies in design and manufacture for construction. By reviewing literature on preassembly (CIB 1993), customisation (Pine 1993) and models for large technical or complex systems (Winch 2003), the research explores the progressive shifts in design and manufacturing that have occurred for five consecutive projects using container based construction. An initial Concept to Order (CtO) project re-using existing containers led to a series of repeat projects, where design effort was progressively minimised through standard design rules for a Make to Order (MtO) product. The final product was a parametric model based on a customised container platform with variable dimensions, and a Design to Order (DtO) package created by combining analysis, design and manufacturing data. This significantly reduced design time to manufacture and led to the prototyping of a Make to Forecast (MtF) modular building product. Containerisation in construction presents a unique manufacturing model; not being tied to the domestic construction market, but supported by a mature international manufacturing base, it can produce large volumes of units over a more sustained period. Therefore a standardised, mass production model should suit this form of production more than mass customisation. However a standardised solution is more limited in its flexibility, and does not provide sufficient variability for most construction projects. An efficient customised design using a shipping container platform became the most effective model, which was based on a Make to Order solution using a Design to Order package based on parametric models.

Keywords

Industrialisation, Design, Manufacturing, Offsite, Containerisation

Paper type

Conference Proceedings

1 INTRODUCTION

Shipping containers are standardised, mass-manufactured re-usable products with a structural form that can be used in construction. Redundant containers can be converted into “ISBUs” (Intermodal Steel Building Units) for self-build housing, exhibition buildings, multi-storey housing apartments and offices, system buildings and mobile architecture (Kotnik 2008). In wider applications containers have also been purpose-manufactured for construction as volumetric units for cellular accommodation and hotels (Kotnik 2008).

The arguments for using shipping containers in construction centre on issues of construction efficiency and sustainability. Buildings can be made more efficiently than traditional onsite construction by making and fitting out purpose-made containers in the factory, and embodied energy can be saved through the re-use of redundant containers.

Containers are re-usable and re-configurable standard building blocks, but they are only a ‘supplement to the existing offer of architecture’ (Kotnik 2008; p 18) rather than being a new building movement. Nevertheless, this research contests that exploring the use of these standardised products in construction, may reveal further how manufacturing and site-based activities can be combined to maximise efficiency.

1.1 BACKGROUND CONTEXT

The inefficiencies of traditional on site construction in the UK have been explored and well documented in government reports and other literature (Latham 1994; Egan 1998; Woodhuysen & Abley 2004). Construction in the UK is characterised by low quality, high costs, a poor safety record, adversarial contracts, low investment in research & development, and poor training, served by businesses operating nationally or locally with low capital investment (Egan 1998).

The efficiencies of industrialisation through standardisation and preassembly have also been well explored (CIB 1998; CIRIA 1999; CIB 2010: Gibb 2000) and have been frequently asserted as a solution to construction inefficiencies. In particular the use of product development as a means of continuously improving a generic construction product using standardised components (Egan 1998) to improve quality, reduce waste, and minimise costs through negotiated supply chains supported by businesses with adequately funded research and training.

The main benefits of standardisation are described as: improved predictability, reliability, improved quality, increased efficiency, improvement to systems and processes, lower costs, reduced waste, and increased opportunity for recycling (CIB 1998). In a similar way, the main benefits of preassembly are quality, cost, efficiency and speed, predictability, safer working practices, and ease of maintenance and replacement (CIB 1998).

However, the complexities of construction continue to pose significant challenges to any pronounced shift from a mostly site based construction process to a manufacturing based process (Gann 1996). In 2005, the proportion of projects using significant levels of manufacturing and preassembly in their construction accounted for less than 5% of the UK market for new buildings and under 2.5% of the total construction market (Goodier & Gibb 2005).

There are several reasons why manufacturing does not suit construction. Unlike most industrialised products there is significant 'client authority' during 'manufacture' stage. The controlled stages of product design, with prototyping and manufacturing stages are replaced in construction by a complex series of design consultation, tendering, prefabrication and onsite activities (Gann 1996; Fox & Cockerham 2000a). Many clients are not interested in the efficiencies of process and standardisation, and will pay more and wait longer for a bespoke building product (Gibb 2000). Furthermore, when a manufactured solution is provided, supply and demand can be sporadic, with little economy of scale, so manufacturers are unwilling to pass on the savings to the client (Gibb 2000).

To date, the most accurate models for construction and manufacture are those from systems production used in large scale and complex industries as found in the power industry, and in shipbuilding. These sectors of the market take advantage of preassembly while absorbing the effects of client led design and the impacts of site based activity (Winch 2003).

By contrast, the standard shipping container follows a more conventional trend in product manufacture with all stages of assembly taking place under factory conditions. To offer customer choice, units are customisable through modularisation (Pine 1993). They use interchangeable standard sub-assemblies with component groupings to create a variety of different transportation units to ISO configuration: standard dry freight container, 'flat-rack' folding containers, insulated containers, refrigerated containers ("reefers"), open top 'bulkainers', open-sided containers for pallet loading, rolling floor containers, 'swap body' containers (with self-supporting legs) and tank container for bulk liquids. All have the support frame, ISO dimensions and corner fittings in common, but they offer the client choice through a catalogue of pre-engineered designs.

1.2 PREASSEMBLY, STANDARDISATION AND CUSTOMISATION

To understand how containers fit into the existing construction industry model, the research looks first at the widely used definitions for preassembly, standardisation and customisation. The following definitions have been used to describe different types or 'levels' of preassembly:

1. Component manufacture – small scale manufactured items or 'loose parts'
2. Sub-assembly – factory assembly of components (semi-finished elements)
3. Volumetric/Non-Volumetric Pre-assembly – factory built units made from sub-assemblies enclosing or not enclosing space (prefabricated/integrated elements)
4. Modular Buildings – units enclosing usable space as part of the completed building

After Gibb (2000) & CIB (2010)

With increased industrialisation of buildings, two basic types of building system have evolved (Groak 1992): contractor-led standard building solutions and manufacturer-led component systems. Although maximizing standardisation and preassembly achieves great efficiency and predictability, the resultant solution limits choice (Gibb 2000) and manufacturers have become adept at offering variations on standardized products, which in a manufacturing environment is described as 'mass customisation' (Pine 1993; Kieran & Timberlake 2004).

Customisation is a ‘process of using standard components or sub-assemblies to produce variety’ (Gibb 2001). Other terms used to describe ranges of standardisation and customisation are ‘Bespoke’, ‘Hybrid’, ‘Custom’ and ‘Standard’. (Fox & Cockerham 2000b). The difference between custom and hybrid is that hybrid contains standard sub-assemblies with bespoke interfaces, whereas custom build has standard components up to assembly level. Furthermore, as well as customisable components and assemblies, buildings include raw or processed ‘formless materials’ that interface with building assemblies on site (Fox & Cockerham 2001). The relationship between these products and types of preassembly is shown in figure 1 and later in Table 1.

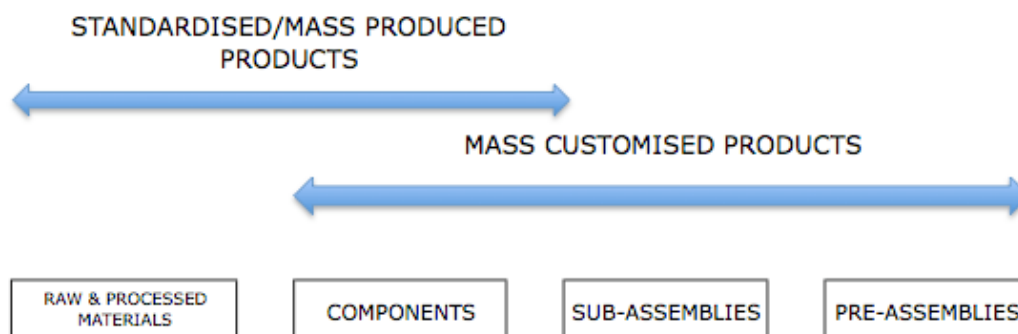


Figure 1: Ranges of Standardised and Customised products combined with levels of preassembly

1.3 COMPLEX SYSTEMS AND MODELS OF MANUFACTURING

Large technical or complex systems such as used in the power industry employ manufacturing as well as having a relationship to site and these systems have been compared to the processes in the construction industry (Winch 2003).

Four generic production strategies can be described (Winch 2003):

1. Concept to Order (CtO): where the client initiates production at the start of information flow.
2. Design to Order (DtO): where a basic product concept already exists, with a significant engineering design work done ‘pre-bid’ and ‘post-contract’.
3. Make to Order (MtO): a fully detailed design that can be configured to the customer’s requirements. The product is ‘customisable’, but there is no additional design work to be done. Material flow starts when the customer makes the order.
4. Make to Forecast (MtF): a product produced to stock and sold either during or after manufacture.

The DtO and MtO strategies happen where there are larger volumes of manufacture, and when clients are shifting responsibility by using less CtO strategies. MtF occurs where there is confidence by the manufacturer that the market demand for a standard product is strong enough to justify producing to stock.

There are three generic production processes associated with these design and manufacturing models (Winch 2003):

1. Procurement, used in CtO strategies, where the information flow for project definition is separated from the detailed design and manufacture.
2. Tender, used for DtO strategies, where the product concept is the customer's specification (employer's requirements).
3. New Product Development, used for MtO (or the variant MtC) and MtF strategies.

Buildings contain many components and assemblies using different production strategies, and the buildings themselves can be described as being on a range of individualised and rationalised building types (CIB 2010). These terms and definitions for building types, products and processes (CIB 2010; Fox & Cockerham 2000b; Groak 1992; Winch 2003) have been collated in Table 1.

BUILDING TYPES CIB (2010)	INDIVIDUALISED BUILDING TYPES		RATIONALISED BUILDING TYPES	
	⇨			
Fox & Cockerham (2000b)	"Bespoke" Building	"Hybrid"/"Custom" Building		Standard Building
PRODUCTION STRATEGIES Winch (2003)	Concept to Order CtO	Design to Order DtO	Manufacture to Order MtO	Manufacture to Forecast MtF
	Mass Customised			Mass Produced
PRODUCTION PROCESSES Winch (2003) Groak (1992)	Procured (Client Led)	Tendered (Contractor Led)	New Product Development (Manufacturer Led)	

Table 1: Terms for Building Types, Production Strategies and Production Processes.

1.4 CHARACTERISTICS OF DESIGN AND MANUFACTURING MODELS FOR BUILDINGS USING CONTAINERS

The research has studied five consecutive projects using purpose made shipping containers as Intermodal Steel Building Units (ISBUs). The following questions were posed with the aim of understanding the characteristics of this form of construction:

1. To what extent are the systems using preassembly levels: raw materials, components, sub-assemblies, preassemblies combined for site assembly and construction (Gibb 2000)?
2. Which production strategies and processes has the system followed through successive projects (Winch 2003)?

2 RESEARCH DESIGN METHODS

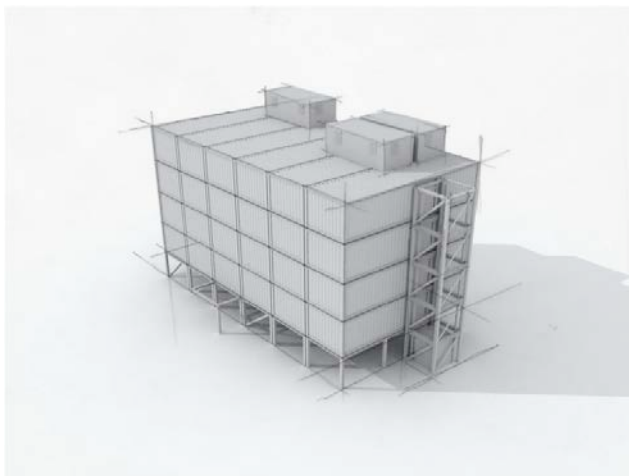
The main approach for the research has been a literature search followed by interrogation of case study project data and 12 semi-structured interviews with clients, product developers and members of the design teams involved in the product development and design of projects.

The case study project data is primary source data generally considered ‘non-reactive’ (Bryman & Bell 2007), having been written for the purposes of the execution of the project and not to hide or emphasise different aspects of the system, and so provides an impartial viewpoint of the case studies. Access was given to most technical and project management data, except commercially sensitive documents such as project cost data and contracts.

The semi-structured interview process was chosen to collect detailed information about the project and to establish reasons for design and manufacturing decisions, providing effective access to the small number of key people involved in every project who held understanding and insights on how the projects evolved (Gillham 2005).

3 PROJECT CASE STUDIES

3.1 GENERAL DESCRIPTION



The five main case studies (A-E) were all budget brand hotels in the UK and this was followed by prototype modular building designs for a European wide hotel brand and temporary worker housing. The modules were produced by the same overseas manufacturer, with all completed buildings the ISBUs being shipped by container ship country to country and container trailer from port to site.

Figure 2: Generic general arrangement of containers with a steel frame ground floor structure and vertical risers

Case Study	PROJECT DETAILS				PROGRAMME & CONTRACT	
	No. of Bedrooms	No. of Units	No. of Storeys	Construction Programme Duration	Procurement	
A	181	86	8	14 months	Contractor led Design & Build Contract	
B	310	181	7	11 months		
C	125	75	6	9 months		
D	84	44	5	10 months	Manufacturer led supplier sub-contract	
E	216	141	7	10 months		

Table 2: Case study project detail, programme and contracts.

Each of the hotels consisted of bedroom units in containers combined with steel frame support for open plan areas, stair cores, lift shafts and service risers.

Units were fabricated in batches of around 75 to 150 units and would typically take one week to fabricate and two further weeks to fit-out. The factory is set-up to fabricate modular products based on normal ISO standard dimensions, with a maximum output of 2000 units per week. A manufacturing bay was set aside for these non-standard units. The requirement for non-standard ISBUs was intermittent, being approximately every 6 months. Fitting out of the units was done in a separate area to minimise any impact on normal manufacturing output.

3.2 DEGREES OF PREASSEMBLY

The degree of completion to the modules was progressively increased through the sequential projects as the design and construction team and manufacturer became more experienced in where efficiencies were possible using offsite techniques.

To show degrees of preassembly, the buildings have been broken down in Figure 3 into elements corresponding to main procurement packages:

- Main Structure (foundations, ground slab, upper frames/slab, lift shaft & risers, stair core, M&E services, roof structures)
- Modules (steel box & insulation, 1st finishes, 2nd finishes, bathrooms, fittings, window)
- Enclosure (external insulation, cladding, roof membrane)
- Each of the elements has then been described in terms of level of preassembly (Gibb 2000; CIB 2010; Fox & Cockerham 2001) and production strategy (Winch 2003)

3.3 PRODUCTION AND PROCESS STRATEGIES FOR CONTAINERS

3.3.1 PRODUCTION STRATEGIES

The end goal for the design and manufacture of the containerised bedroom modules is to arrive at a Design to Order (DtO) package with a maximum of preassembly and a Make to Order (MtO) production. For the main structure and envelope there is a similar aim to minimise design effort through DtO packages and to maximise preassembly but, for both of these areas of the building, there are limitations to the degree to which customised solutions can be provided. The elements of the building related to site conditions needed to be designed from concept (CtO) due to the many unknowns and potential variations. Although technical solutions to the cladding and roofing elements using efficient production techniques and customisable solutions could be created, the influence of local planning conditions and approvals may mean that these elements are redesigned from concept (CtO) for each project, or at least by development of an existing DtO cladding solution.

Assessing the production strategies at the more detailed level of materials, components and assemblies, the research identified that raw and processed materials were 'Made to Forecast' MtF (sheet steel, plywood, insulation, plasterboard, paint). Some components were 'Made to Forecast' MtF (corner castings, connection bolts, waste pipes, bathroom fittings, conduit, wiring and doors). These were all small scale components. Larger components were 'Made

to Order' MtO (connection plates/locating pins) as were subassemblies (unit frames) and pre-assemblies (completed steel modules).

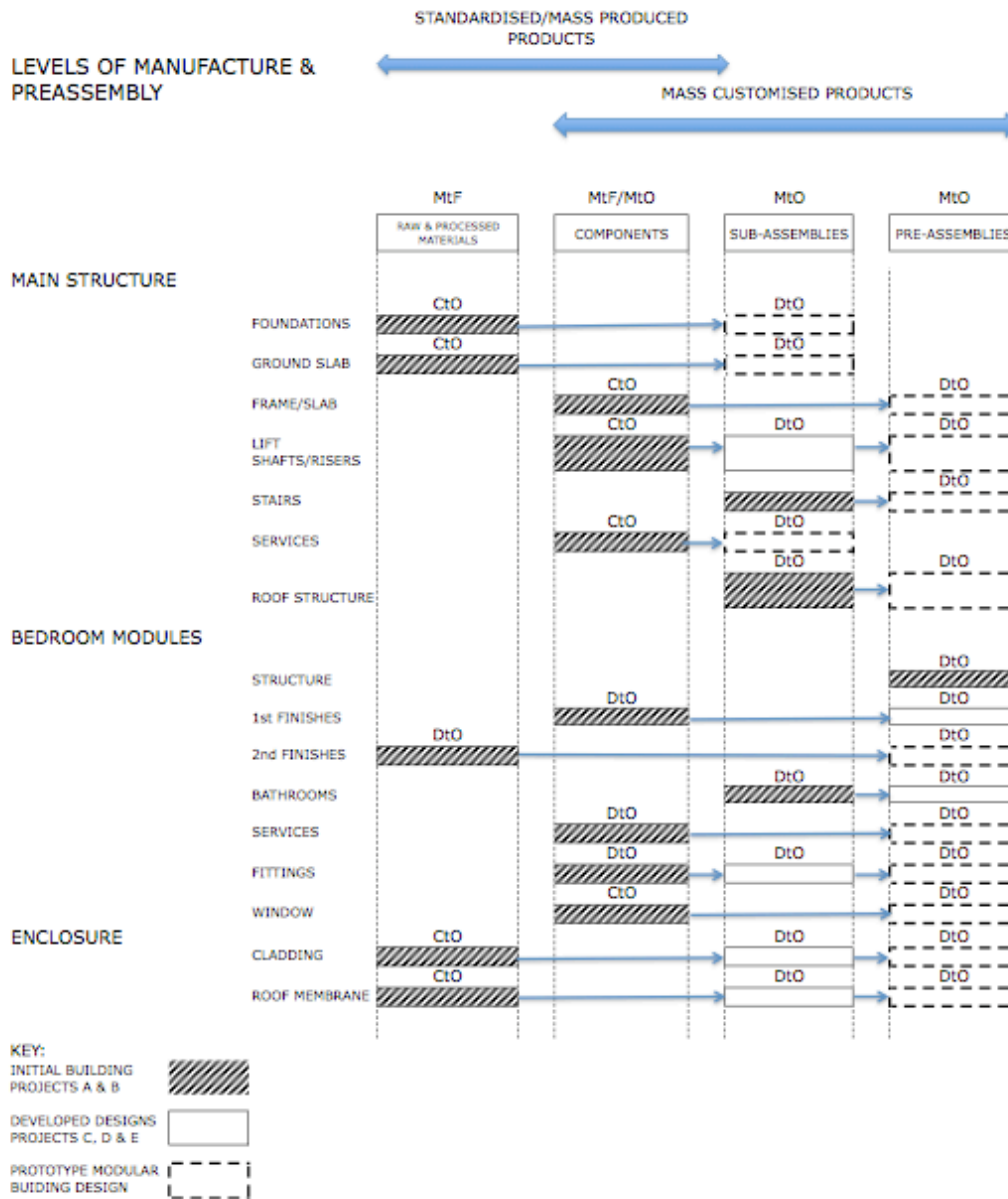


Figure 3: Development of preassembly levels for the different construction elements in a series of case study projects.

The other elements of the building that remained 'Concept to Order' CtO on all the initial and developed building designs were the general arrangements for the buildings, loadings and structural analysis, and utility connections. The dimensioning and detailing of the modules started as 'Concept to Order' CtO in the first projects but became a 'Design to Order' in later developed designs. The module design dimensioning and detailing became more efficient through the development of design manuals, calculation routines and analysis linked to parametric CAD models of the units.

3.3.2 PROCESS STRATEGIES

Case study projects A & B were tendered as a Design & Build contract and awarded to a main contractor working with the manufacturer supplier. Prior to project A, the same contractor/manufacturer team had collaborated on a smaller trial project, where they tested out the practical performance of the units, but this project was the first large scale deployment of the system. Although Project A was a tendered Design & Build contract, in several ways it was a New Product Development project with client design authority and could be described as Concept to Manufacture (CtM) variant (Winch 2003), although commercial risk stayed with the main contractor.

Case study project B had some client-led aspects but it followed more closely the DtO/MtO model with a tendered design & build contract. Case study projects C to E were manufacturer-led DtO/MtO tendered sub-contracts to a main contractor; there was no client input.

3.4 MASS CUSTOMISATION OF CONTAINERS AND MODULAR BUILDINGS

As successive DtO/MtO projects became more refined and efficient, the product developer/manufacturer team were searching out further opportunities for increased efficiencies in manufacture and construction. The manufacturer, being a high volume producer, was keen to develop a more standardised mass produced building product and started to explore Manufacture to Forecast scenarios, but discovered that site conditions and market conditions still favoured a MtO product with the possibility of customisation rather than a MtF product. Also, the MtF product only showed marginal costs savings on MtO.

4 CONCLUSIONS

Containerisation in construction presents a unique production model; not being tied to the domestic construction market, but supported by a mature international manufacturing base, it can produce large volumes of units over a more sustained period.

Production and process strategies from complex and large-scale industries provide useful models for analysis of construction projects that involve increasing levels of manufactured products. In this case the manufacturer favoured a more efficient Made to Forecast model for his production facility, but found that the degree of standardisation limited its flexibility for use, and instead an efficient Made to Order solution was progressively established using a refined Design to Order package using parametric models.

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APPENDIX D OFF-SITE CONSTRUCTION IN SUPPLIER-DRIVEN AND CLIENT-LED SCENARIOS (PAPER 4)

Full Reference

Robinson, A.C., Gibb, A.G.F., Glass, J., Austin, S.A., (In review). Off-site Construction in Supplier-driven and Client-led Design Scenarios. *International Journal of Construction Management*.

Abstract

Although off-site construction is a sustainable form of construction it remains a minority method despite a willingness by contractors to consider alternative methods. Policy makers in the UK and other parts of Europe are refocusing attention on standard supplier-driven solutions, but there are few case studies to demonstrate how these work in practice. This study examines recent hotel building projects to compare supplier-driven and client-led design scenarios. The research verifies the production conditions and processes of each project and measures the degree of preassembly against production strategies to establish the degree of supplier driven design. The case studies evidence a link between high commoditisation and supplier-driven off-site methods, but even in these scenarios, clients still prefer contracts with a main contractor and not directly with suppliers.

Keywords

Off-Site, Standardisation, Supply-Chain, Design, Client

Paper Type

Journal Paper

1 INTRODUCTION

It is widely acknowledged that off-site construction (Zhai et al 2014), also referred to as prefabrication (Anderson & Anderson 2007; Jaillon & Poon 2014; Tam et al 2014), is a very sustainable form of construction. Increased levels of preassembly (Gibb & Pendlebury 2006; Lam et al 2006; Arif & Egbu 2010) reduce the inefficiencies of on-site work; notably there is reduced waste (Tam et al 2006, 2014), a reduction in health & safety risks (Gibb 1999, CIC 2013) and a lower environmental impact on the site itself (Gibb & Isack 2003; Pan & Sidwell 2011).

Off-site methods usually mean much faster assembly on site, and it seems that many contractors are considering their use (Steinhardt et al 2014). However an increase in off-site methods has been anticipated for some time (Goodier & Gibb 2007) and still only a minority of contractors regularly use these methods. This is a trend that is repeated across many countries (LeBeau & Viñals 2003).

The reasons cited for cautiousness with off-site methods are: higher fabrication costs, concerns over quality, a lack of market stability for manufacturers, longer lead-in times, limitations in standardisation and design flexibility, more complex interfaces and a requirement for different skills compared to more conventional construction techniques (Goodier & Gibb 2007; Nadim & Goulding 2011).

Precise figures on the proportion of offsite methods are difficult to acquire, and there are differing opinions on what constitutes off-site construction (Goodier & Gibb 2007). In the UK, estimates vary between 2 to 6% (Goodier & Gibb 2005, Taylor 2009, Research Markets 2012; Goulding et al 2014). These are low figures, and the focus in the UK and other European countries is to explore the potential of greater input by suppliers (Cabinet Office 2011) who can offer design and delivery product service solutions. Some have suggested that supplier-driven designs, with the use of more integrated data systems (Owen et al 2010; Rekola et al 2010) and enhanced interfaces between elements (Thuesan & Hvam 2011) will bring about a step-change in construction practices (van Nederveen et al 2010; Goulding et al 2014; Farr et al 2014).

In this alternative to the conventional client-led approach (van Nederveen et al 2010), the building designs start from a performance specification, with the supplier's building system offered as the integrated product solution to meet the client's objectives. Supplier-driven buildings could lead to even more sustainable practices (Pearce & Ahn 2013) with buildings becoming dematerialised into a series of services instead of physical products. However, there is little data from industry to show how this might work in practice. This study measures levels of off-site and on-site construction on standard type hotel buildings to compare client-led and supplier-driven design scenarios and then uses project team interviews to find the motives for adopting different design, procurement and construction scenarios.

2 MEASURING SUPPLIER-DRIVEN CONSTRUCTION

The term off-site is defined as the manufacture and preassembly of components, elements or modules before installation into their final location (Goodier & Gibb 2007). In nearly all cases projects are a combination of off-site and on-site methods, and the two methods are considered and measured together in this research. Links in this assessment are also made to production processes since the economies of standardisation applied to mass production or mass customisation are often associated with off-site methods. Production processes for construction materials can be classified as either stock items that are made to forecast (MtF) or non-stock items that are made to order (MtO) (Winch 2003).

The following definitions and production strategies shown in Table 1 have been used for the assessment of off-site and on-site methods in this research.

	Definitions	Production Strategy	Building Fabric Materials & Products
1.	Raw & Processed Materials (Fox et al, 2001; Eekhout, 2008)	MtF (Winch 2003)	Hot-rolled and cold rolled steel plate & profiles, standard lengths of deformed reinforcing bar, ready-mixed concrete & mortar, bricks & blocks, standard lengths of timber, sheets of plywood, plasterboard and insulation panels, glass blocks & cement render.
2.	Components (also referred to as 'loose parts') (Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	MtF/MtO (Winch 2003)	Raw and processed materials (1) with further processing. Fabricated steel sections, castings and connections, cold-formed steel elements, pre-bent deformed steel bars, pre-cut timber and boards, structurally insulated timber panels (SIPS), clamps & stick system cladding, glass panels.
3.	Subassemblies (Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	MtO (Winch 2003)	Raw materials (1) and components (2) combined off-site. Welded & bolted steel frames, cold-formed steel frames, prefabricated steel reinforcement cages, hybrid pre-cast concrete elements for further casting on site (e.g. twin-wall & 'Omnia' slabs), framed glass panels, rain screen cladding.
4a.	3D Volumetric & 2D Non-Volumetric Preassemblies (Gibb & Pendlebury 2006; Arif & Egbu 2010; Girmscheid 2010)	MtO (Winch 2003)	Raw materials (1), components (2) and subassemblies (3) combined off-site. Insulated & boarded steel frame panels, pre-cast concrete panels & slabs, insulated timber frame panels, panelised glass cladding, composite insulated panels & curtain walling, complete frame assemblies.
4b.	Pods (Gibb & Pendlebury 2006)	MtO (Winch 2003)	Raw materials (1), components (2) and subassemblies (3) made into integrated and fully serviced small enclosed assemblies, non-loadbearing, in timber, steel and composite panel, e.g. bathrooms.

Table 1 Definitions of on-site and off-site processes and products

A model for quantifying levels of standardisation in client-led versus supply-driven construction (van Nederveen et al 2010, p242) is shown in Figure 1. The Traditional/Design-

Build-Finance-Maintain-Operate (DBFMO) and ‘Living Building Concept’ (LBC) scenarios articulate some existing bottom-up and top-down drivers that are present in construction when levels of off-site are being considered.

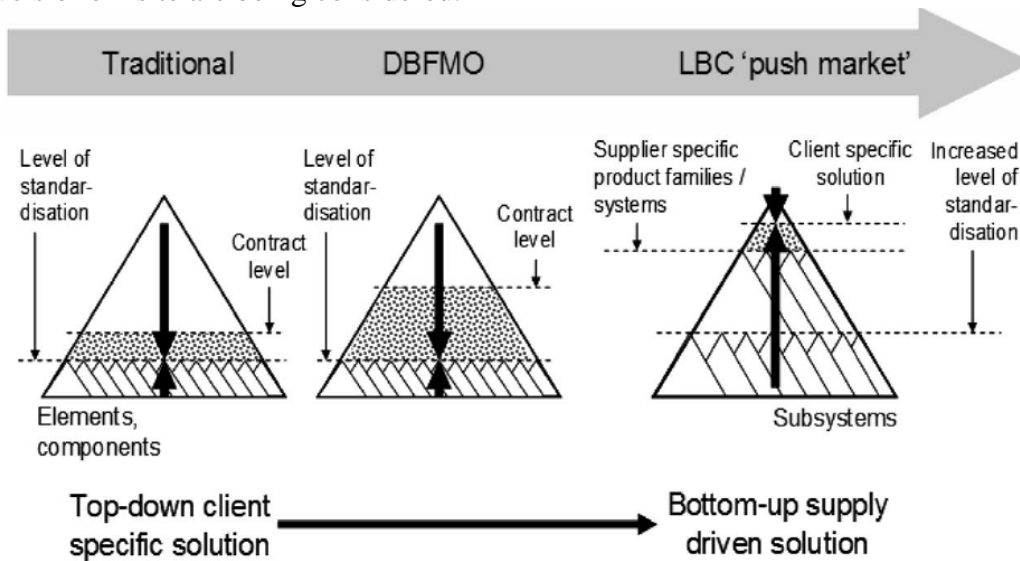


Figure 1 Demand-driven and supply-driven construction (van Nederveen et al 2010, p 242)

The more commonly encountered top-down client-led solution constrains the degree of integrated industrialised components through a late contractual decision leading to low levels of standardisation. Conversely, the bottom-up, supply-driven solution allows a higher degree of product integration and sub-systems. The efficiency in the supply-driven model comes from a function-driven supply-chain of product service solutions and is offered to the client in combination with a site-specific solution.

Assuming that a top-down client-driven scenario leads to a larger proportion of raw materials and small components, and a bottom-up supplier-driven scenario leads to a greater degree of sub-assemblies and preassemblies (van Nederveen et al 2010), figures 2 and 3 show generalised diagrams of combined material flows for these two scenarios. The black arrows represent the flow of raw materials to factory, and the white arrows indicate flow of materials and products to site. The thickness of the arrows on the diagrams represents the proportion of material and product flows.

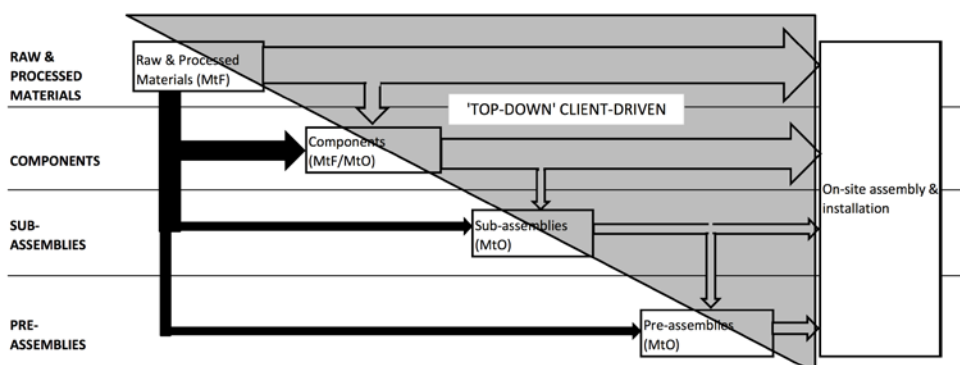


Figure 2 Generalised material flows for a top-down/client-led scenario with extensive on-site assembly

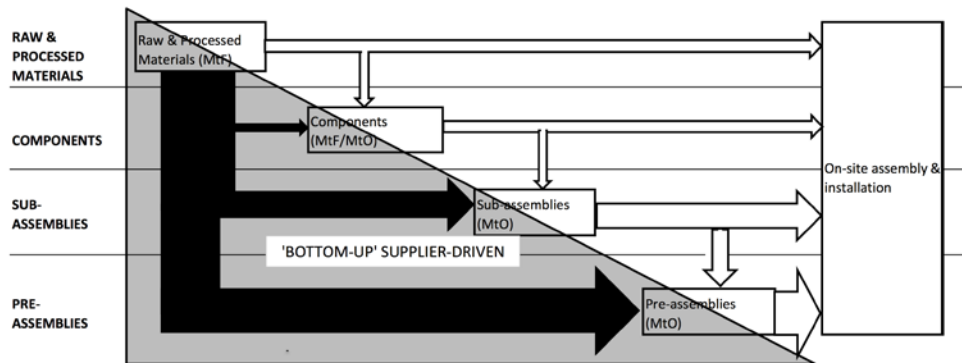


Figure 3 Generalised material flows for a bottom-up/supplier-driven scenario with more extensive use of preassemblies

These assumptions for quantitative proportions of raw materials, components and larger preassemblies in the client-led and supplier-driven scenarios are considered in the following research along with other motives for selecting off-site construction.

3 RESEARCH DESIGN

This research takes case studies from design practice where a range of approaches and construction systems have been applied to several series of construction projects for the same building type. The projects are divided into two groups: Group A are supplier-driven, which in this case involves a volumetric manufacturer, and Group B are client-led projects, where a single client is working with several different contractors and their suppliers. An empirical measurement of the degrees of off-site is quantified and presented in a graphical format to demonstrate the different production techniques. This deductive approach is followed by an inductive phase to draw generalisable inferences (Bryman & Bell 2011) from team interview data (Gillham 2005).

The research is therefore multi-methodological (Fellows & Liu 2009) with a combination of quantitative and qualitative methods chosen due to the complexity of the research variables, and what is perceived as an interpretation crossing different fields of inquiry (Cresswell 2003). The research position is critically realist, and epistemologically constructivist because the structure of events and discourses are partly revealed through the research (Bryman 2012). The issue of design standardisation is believed to be complex, and examples offered through a case study method are unlikely to lead to simple problem solving. However, they are also unlikely to stray too far from an objective position. Therefore, ontologically, the research measures what are known to be objective realities concerning the different project scenarios.

4 HOTEL BUILDING CASE STUDIES

Figure 4 shows a typical plan for a standard hotel building; overall plans vary in shape and scale but there are very few changes in the layout of standard bedrooms. Up to 85% of a floor

area is a repeated layout of bedrooms, bathrooms and service risers. Room access is along central corridors with services distribution running in the corridor ceilings. The remaining 15% of floor plates contain stairs, lifts, linen rooms and main service risers.

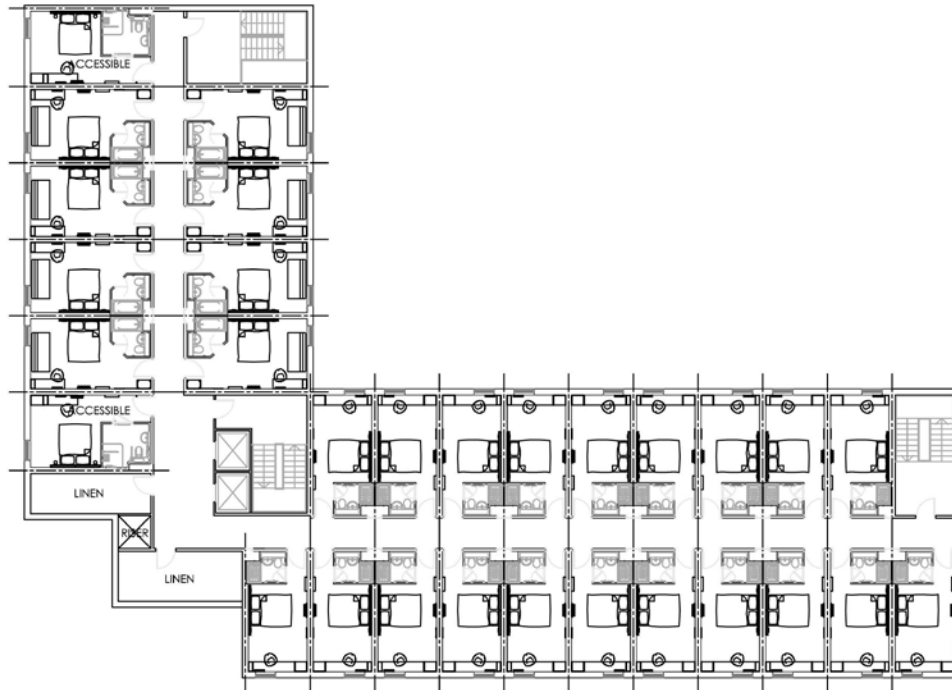


Figure 4 Typical hotel building layout (Travelodge Hotels)

The eight case studies are classified in Table 2 grouped under their general characteristics: external factors, project teams, project processes and project brief (Harper 1990; Belassi & Tukel 1996). Characteristics include the number of occurrences (Gibb 1999), the building type, its function and size. External factors take account of the urban site environment (Gibb 1999; Lam et al 2006) and architectural building type (Chen et al 2010; Winch 2011). Project team organisation is assessed in terms of continuity of the main actors (Nam & Tatum 1997; Erbil et al 2013). An assessment of project processes considers procurement method, timing and choice of construction material and methods (Gibb 1999; Chen et al 2010; RIBA 2013). The final category on briefing criteria is added to assess clarity of brief, budget, financial model and duration of construction programme (Blismas et al 2006; Winch 2011). These characteristics are summarised to identify differences between the two sets of data.

FACTORS	PROJECT	A1	A2	A3	A4	A5	B1	B2	B3	
PROJECT RELATED FACTORS	Occurrences	5 out of 50 (Repeat)					3 out of 5 (Series)			
	Type/Function	Low-rise Budget Hotels					Medium-rise Business Hotels			
	Nature/ Volumes	Open plan reception, accommodation cellular			Bedrooms extension, accommodation cellular		Open plan reception, restaurants & business centre, accommodation cellular			
	Number of floors	8	7	6	5	7	10	14	10	
	Of which are bedrooms	6	6	5	5	7	8	11	7	
	Number of bedrooms	181	310	125	84	44	256	330	450	
	Size of Project	6,500 m2	9,765 m2	4,050 m2	2,270 m2	1,390 m2	8,640 m2	12,500 m2	17,350 m2	
EXTERNAL ENVIRONMENT FACTORS	Physical Environment	Urban Constrained	Non-Urban		Non-Urban Constrained	Non-Urban Constrained	Urban	Urban Constrained		
	Architecture	Specification-led					Specification-led/Iconic			
PROJECT TEAM	Client Body	Client 1 (Hotel Chain Franchisor)					Client 2 (Hotel Developer/Owner/Operator)			
	Architecture	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5	Arch 6	Arch 7		
	Engineering	Engineer 1					Engineer 1			
	Contracting	Contractor 1	Contractor 2	Contractor 3	Contractor 4	Contractor 5	Contractor 6			
	Manufacturing	Manufacturer 1					Manufacture 2	Manufacturer 3	Manufacture 4	
PROJECT PROCESSES	Procurement	D & B (single stage)					D&B (two stage)			
	Construction Decision	RIBA Stage E Detailed Design			RIBA Stage F Production Information		RIBA Stage F	RIBA Stage E	RIBA Stage E	
	Construction Method	Steel frame, steel volumetric modules, plasterboard					Pre-cast- Concrete	Insitu-Tunnel Form	Hybrid - Twin wall	
BRIEFING CRITERIA	Brief Definition	Tame					Ill-defined	Developing	Tame	
	Project budget	£10m	£15 m	£6 m	£2.7 m	£1.7 m	£22m	£32m	£33m	
	Rate	£1200-1600/m2					£1800-2100/m2			
	Financial Model	Capital Cost Driven					Capital Costs/running costs			
	Construction Programmed	14	11	9	10	10	18-24 months (estimate)			

Table 2 Commissioning characteristics of projects in Groups A & B

Although the budget hotels share similarities in general layout there are some differences. Both sets of projects are from a series, and the group B projects are generally larger, and found in more compact urban sites, but the main differences concern the client approach to contractor and supplier involvement. The first set of projects (A) are let under a single stage tender, and the selection of the volumetric supplier is decided before the main contract is let, with the contractor being invited to submit a tender that included the supplier's proposal. With the second set of projects (B), the construction type is decided via the appointment of the main contractor, using a two-stage design and build tender process.

5 MEASURING MATERIAL FLOW THROUGH LEVELS OF PREASSEMBLY

Table 3 and Figure 5 show material quantities and flows for the building fabric of the typical bedroom layout areas in building type A. A similar volumetric unit was used for all projects A(1) to A(5). The bathroom is included as a separate quantity. Cladding, other building services and internal fit-out items are omitted for clarity.

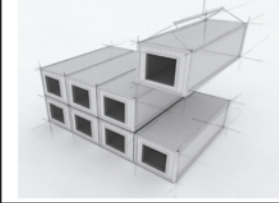
	Raw & Processed Materials		Components		Sub-assemblies		2-D Pre-assemblies		3-D Pre-assemblies	
	kg/m2	%	kg/m2	%	kg/m2	%	kg/m2	%	kg/m2	%
Steel coil, plate, wire	-	-	-	-	-	-	-	-	52.33	34.8%
Steel Sections	-	-	-	-	15.41	10.3%	-	-	-	-
Plywood	3.42	2.3%	-	-	-	-	-	-	32.53	21.6%
Plasterboard	1.90	1.3%	-	-	-	-	-	-	12.75	8.5%
Sound Insulation	-	-	-	-	-	-	-	-	2.85	1.9%
Castings	-	-	5.52	3.7%	-	-	-	-	-	-
Bolts/connecting plates	-	-	0.76	0.5%	-	-	-	-	-	-
Bathroom									22.83	15.2%

Table 3 Material mass per m2 and percentages relative to total construction for different levels of preassembly in case study A1

Less than 5% of the materials for the superstructure of the bedrooms arrived on site unprocessed and at least 95% had been preassembled before arriving on site.

CASE STUDY A
STRUCTURAL MATERIALS FLOW

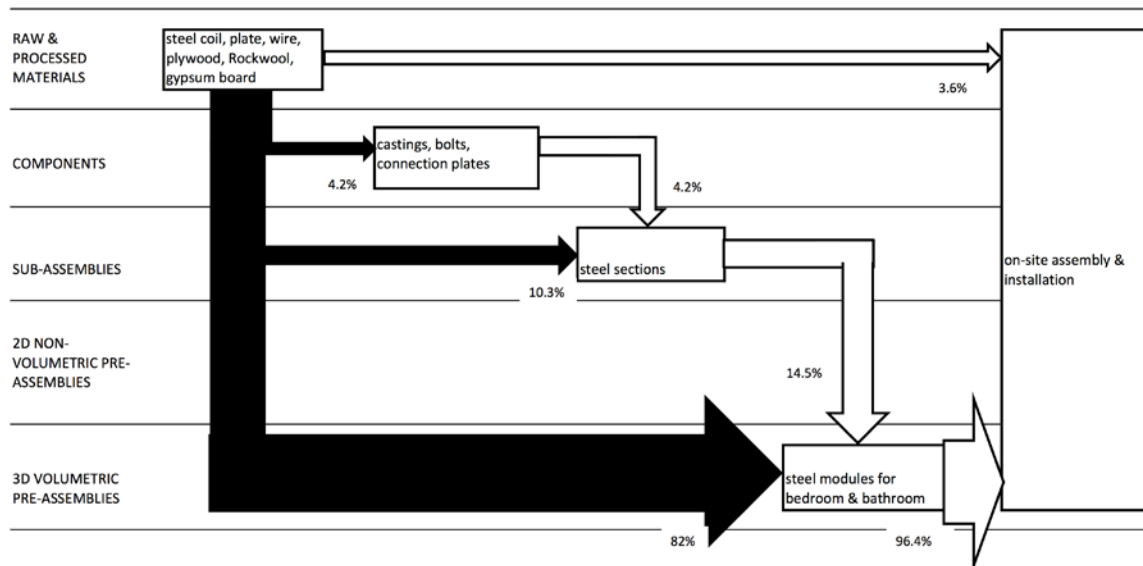


Figure 5 Material Flow for typical Case Study A1 – Volumetric Steel bedrooms with integral bathrooms

Table 4 and Figure 6 show material quantities and flows for case study B(3): a hybrid off-site/on-site construction. These case studies present a more balanced scenario of on-site and off-site processes, although other examples had more or less off-site work.

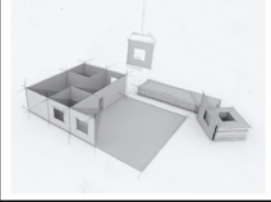
	Raw & Processed Materials		Components		Sub-assemblies		2-D/3-D Pre-assemblies		Pods	
	kg/m2	%	kg/m2	%	kg/m2	%	kg/m2	%	kg/m2	%
	Insitu concrete + reinforcement	536.77	41.9%	30.61	2.4%	-	-	-	-	-
Thin pre-cast walls & slabs + reinforcement	-	-	50.36	3.9%	614.16	47.9%	-	-	-	-
Bathroom	-	-	-	-	-	-	-	-	49.47	3.9%

Table 4 Material mass per m2 and percentages relative to total construction for different levels of preassembly in case study B3

CASE STUDY A
STRUCTURAL MATERIALS FLOW

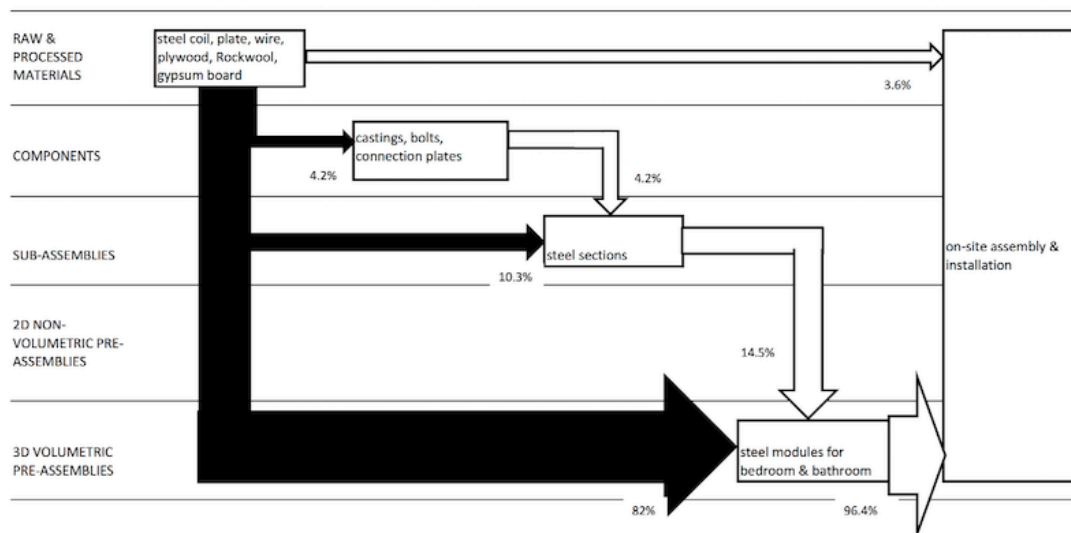


Figure 6 Material Flow for typical case study B3 – Hybrid precast/insitu concrete room with a bathroom pod.

6 FINDINGS FROM PROJECT DATA AND PROJECT TEAM INTERVIEWS

6.1 CASE GROUP A – MODULAR CONSTRUCTION BUDGET HOTELS

All the hotels are built using the supplier’s steel volumetric product and the bedrooms as supplied in the modules are responding to tightly defined specification: a technical specification for detailing performance requirements in the bedrooms and general access areas. Termed the “brand standards manual” the document included statements about general robustness of construction including clauses on sound and vibration transmission between rooms.

An interview with a budget hotel client (A) shows that, although they had agreed to the use of an off-site volumetric product, they were not interested in the technique except as a way of meeting their cost and programme objectives.

“A bedroom looks like the bedroom as it should be. It doesn’t matter if it is concrete, or steel boxes. It’s just a brand...” (Client A).

The client is focused on the commodity “branded” product, and not in the construction with its process of assembly.

“...projects are at the (low-budget) end., their financial model doesn’t allow for creativity; they rely on standardisation in design, whether built traditionally or (using) off-site methods” (Designer D; A2).

Price is the over-riding factor; any efficiency of production technique is secondary to capital cost. The architect’s brief for all buildings was similar: to create a hotel plan that maximised the number of standard rooms on a plot while meeting minimum planning requirements with respect to building frontages and height limits. The hotel operators needed a building that filled the site, not a building with geometry defined through standard room sizes. This meant that there were variations in module widths, heights and other adjustments, and the production systems needed to be able to accommodate variations in module size.

The manufacturer would have preferred to be directly appointed by the client, but in all the contracts the units only accounted for 30 to 40% of total project value, the remainder being ground works, construction, servicing and fit out of non-bedroom areas, cladding and external works. The client chose a single commercial entity to take on project risk, and the main contractor was the only one who would do this.

6.2 CASE STUDY B – BUSINESS HOTELS

The client in group B was operating five hotels and did not have a standard manual for the hotels but they were very closely involved and “hands-on” (Designer K; B3) with the design and construction process.

“...there was always a representative from (the client) at all the meetings and they were extremely vocal about what they wanted” (Designer J; B2).

The clients managed the process of standards and transfer of knowledge by taking a lead in the meetings, with consecutive designs becoming “enhanced and refined” (Designer J; B1).

“They knew exactly what they needed, what adjacencies, how much room they needed for cleaning, everything was given ... in a series of weekly discussions...” (Designer J; B2).

“...we had done a hotel before, (client B) had a set of drawings, and they asked us to do something similar, but.. better..” (Designer J; B1)

The brand was expressed orally through the meetings and it existed on drawings from the previous projects. The designs being “an evolving thing” (Designer J; B1) led to a slightly modified design for each building.

The construction methods varied for each project in group B, and were largely dependent on the preferences of the contractor who was awarded the contract, based on their overall commercial offering. The client showed little interest in the detailed construction method, except they insisted that the buildings had to be made of concrete. The client would not consider any lightweight alternatives due to concerns over sound insulation. They also had concerns that plasterboard walls, normally associated with framed construction could be too easily damaged and so specified painted concrete walls.

7 IMPACT OF TIMING OF PROCUREMENT ON CHOICE OF CONSTRUCTION METHOD

Most group A projects, which were procured early, had a programme suited to a higher degree of off-site resulting from supplier-driven design development. The timing and degree of off-site in case study B projects were more varied. Interviews for group B projects reveal that the teams encountered problems due to a lack of alignment between the construction methods and the design. For example, in project B1 the original contractor for the first stage was rejected at the second stage and a new contractor was brought in to build the scheme. Furthermore, although they joined late in the pre-construction programme stage, the new contractor proposed a precast method that required significant re-design and led to problems with its constructability.

“The problem with (project B1) was that there were some areas where it didn’t really suit precast. Bedroom modules that were trapezoidal... there were bits of insitu to resolve and that sort of thing... and there were other areas that did not go well” (Designer J; B1).

The decision to use an off-site method at a late stage of the project led to a mismatch between building layout and the efficiencies of the construction product.

In theory, a two-stage tender process should allow the construction team to collaborate in the earlier phase of the detailed design (Gibb 1999), but this was not the situation found in these projects.

“There was very little input from (Contractor 2) between 1st and 2nd stages”. (Designer J; B2)

“..(Contractor 6) were slow to be appointed and slow to bring in their subcontractors. The two-stage tender process didn’t work very well... they didn’t offer much input, and not until they were fully appointed (at 2nd stage)... and then only when the 'subbies' were involved to flush out the final design...” (Designer L; B3).

The designs proceeded to a detailed stage without input from “subbies” (subcontractors) who would have been able to offer detailed information on the practicalities of particular construction methods.

8 DISCUSSION

Low cost accommodation buildings are a significant market for standardised building products, and the link between the use of higher levels of preassembly with supplier-driven designs has been examined in this research. Despite a standard building typology and a high level of off-site volumetric construction being used, the manufacturer was not able to offer a commercial solution for the majority of the building.

The client who was more engaged in the design and construction process for the second group of projects showed greater concern for quality of the final design outcome, although the two-staged procurement method due to its timing, seemed to limit take-up of off-site methods. Previous literature has identified that design and build contracts can be problematic for design coordination (El. Reifi & Emmitt 2013); this research shows that multiple-stage design and build, a procurement method intended to improve contractor engagement in the early stages can in some cases, create additional problems due to the lack of a financial commitment until the later stages of the contract making an informed choice about off-site manufacturing method even more difficult.

9 CONCLUSIONS

A supplier-driven scenario is unlikely to be widely accepted unless complete buildings are offered, and in the absence of these services a main contractor still seems to be the preferred way for clients to control their commercial risk, which in turn dictates the methods of construction chosen (Gibb & Goodier 2007). The reluctance of the hotel client to consider a steel framed construction suggests that there is a problem of perception within the hotel sector for more lightweight construction methods, which calls for further independent research.

The findings suggest that a supplier-driven scenario is only one part of the overall picture for procurement practices. Manufacturers must be prepared to deal with the more ad-hoc nature of client-led commissions since this continues to be a significant part of the overall industry picture.

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APPENDIX E 'REINVENTING THE WHEEL?' – CASE STUDY RESEARCH INTO LINEAR/NON-LINEAR & FRAMING PROCESSES (PAPER 5)

Full Reference

Robinson, A.C., Gibb, A.G.F., Austin, S.A. 'Re-inventing the wheel?' – Case Study Research into Linear/Non-Linear & Framing Processes. Proceedings of the 29th Annual ARCOM Conference, 2013, September 2nd – 4th, Reading, UK

Abstract

'No need to reinvent the wheel' and 'it's just painting by numbers' are expressions used by designers avoiding unnecessarily complex or over-simplistic approaches to design problems. These are extreme scenarios, but practitioners are under increasing pressure to minimise design effort and rationalise designs through repeated application of standardised solutions. This paper deductively tests and analyses interview data from building design case studies against analytical, conjectural and reflective theory models for repeat design solutions. A re-framing process for both clarifying a brief and selecting a design solution is shown to best match the described designer behaviour, with instances of linear analytical and non-linear conjectural processes occurring within that framework. It is inducted that designers in a repeated design adopted a strategy for rationalising the design, which they described as 'modularisation', although this had multiple meanings for different members of the design team. The strategy was driven in part by the ability to use parametric CAD models to duplicate the design. The case study data is based on a series of architecturally sophisticated projects with fairly unique standardised characteristics. This may therefore limit the ability to generalise these findings to more rationalised building types. However, the conclusions of this research add to the understanding of approaches adopted by designers using pre-solutions for standardisation.

Key words

Client, brief, framing, design, efficiency, standardisation, modularisation

Paper Type

Conference Paper

1 INTRODUCTION

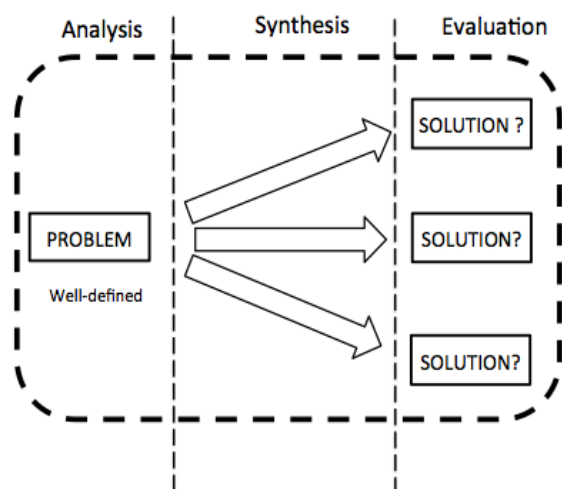
'Reinventing the wheel' describes an activity that wastes time and effort, because it creates something that already exists (OED, 1989). However, there is a presumption in the use of the term wheel, that the problem to be solved is tangible and has discrete, definable parameters. In building designs, problems are more complex and interdisciplinary, and it is sometimes necessary to adopt a more 'inventive' approach (Lawson 2006). Paint-by-numbers is the very opposite of invention. Devised as a process for mechanically creating a copy of an original artwork (Palmerpaint, 2013) the expression refers to an activity that is unimaginative or unnatural (OED, 1989). The 'artist' does not require significant knowledge of the original process or the artistic intention. Within the construction industry, when an outcome is necessarily rationalised and is repeated many times, a mechanical or industrial approach may be the most appropriate because of it offers consistency, speed and efficiency (Womack et al 1990).

This study analyses case study data considering reflective processes of design, described in literature as framing (Schön 1983; Atkin 1992), and compares these to more analytical and conjectural approaches.

The case study considered for this research is a large-scale infrastructure project with several repeat designs: a series of high-speed railway stations, using a prototype station design with four specific designs developed simultaneously from the base design. The design team aimed to rationalise the process through the generic design with standardised components, sub-assemblies and pre-assemblies with parametric data using a shared Building Information Model. The team collectively described the process of prototyping, rationalisation and use of generic components as 'modularisation'.

2 DESIGN STRATEGIES

According to Zal & Cox (2008); p3 'Prototypical strategies' will avoid 'completely reinventing the wheel' when working with manufactured products. The same phrase is used when adopting 'typologies' from past solutions as design generators (Emmitt 2002; p122).



Linear
(Pugh 1990; Cross 1990)

These both suggest that there are ways of finding design solutions more quickly. As will be defined below, the use of previous solutions is just one of several methods used in design, with analytical techniques being used for well defined problems and conjectural techniques being used for ill-defined problems.

Problem-solving Design Theory

Concept, feasibility and detailed design are dynamic and creative phases of a design process and many models have been proposed (Austin et al 2001). Designers follow sequential steps and iterative cycles of design, although others argue (Lawson 2004) that a reflective process is more

accurate description. Design methods and design science have been subjects of research since the 1960's (Bayazit 2004). Described as a separate discipline - a 'designedly way of knowing', thinking and acting (Cross 2001) - designers are trained heuristically to evolve processes to solve problems that have not yet been encountered (Lawson 2006). Designers tend to be solution focussed accumulating knowledge they may use in later designs. Furthermore, the process from problem to solution is not consciously followed or straightforward (Lawson 2006).

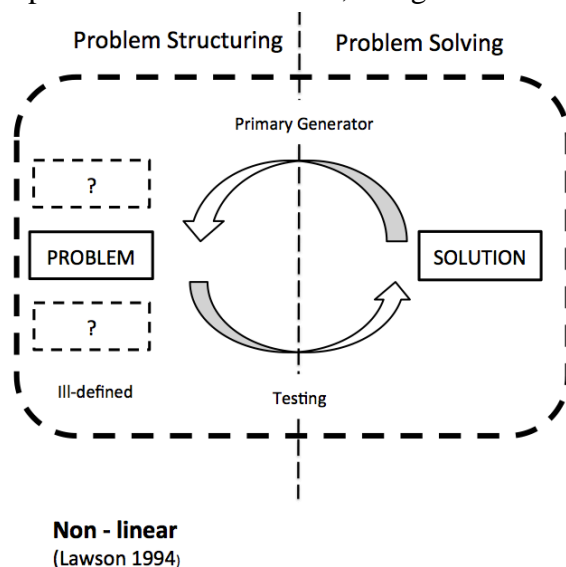
Figure 1: Linear problem solving

Usually working to a time limit, designers aim to generate a satisfactory solution rather than instigate a prolonged analysis of a problem (Cross 1982). The more experienced rely on skilled behaviour reviewing many levels of design simultaneously, tacitly ignoring non-important issues (Cross 1982) knowing that it is impossible to assimilate all the constraints (Cross 1982). Solutions may emerge through intense team deliberations (Macmillan et al 2001) and therefore, as a result, designers do not necessarily 'know' how they design.

Linear and Non-linear processes

For well defined problems, a linear process with cycles of analysis, synthesis and evaluation, (Pugh 1990, Cross 1990), is the most common model. In complex designs several competing solutions are investigated (Harper 1990), and an objective assimilation of the options is used to find the best solution (Figure 1).

If problems are ill defined, designers tend to use a more conjectural process: a cyclical non-



linear model with problem structuring and problem solving (Lawson 1994), using a primary generator and testing process as shown in figure 2. The primary generator or 'proto form' is a way of short-circuiting an otherwise complex activity.

It has been recognized that, even in a linear design process, building design solutions may consist of overlapping and conflicting systems and sub-systems of components and assemblies (Groak 2002) further complicating the design process.

Figure 2: Non-linear problem solving

Schön (1988) questions the positivistic view on design, noting that most designers are responding to ill defined problems, using

intuition to deal with uncertainty and conflicting demands (Cross 1981). Therefore, the model of assimilation, synthesis and evaluation may be an inadequate description of the process (Lawson 2006) and, in any case, is not practiced widely (Atkin 1992).

Framing Process

Framing theory proposes that each building design is a mental frame (defining size, layout, architecture etc.), which acts as reference for future development of ideas (Atkin 1992). Architectural design is a form of experimentation (Schön 1983); the framing of a problem is like a hypothesis to be solved through the design process. Framing defines boundaries and

situations and is used as a way of describing generic perspectives (Schön 1983; Atkin 1992), leading to framing also being used in establishing building types.

However, research on design thinking and framing (Atkin 1992) has shown that this approach can lead to stereotyping. Atkins asserts that most designs are limited to a small number of generic design options, and ‘experimentation involving conjecturing and rigorous refutation is not popular amongst designers’ (Atkin 1992); p129. Usually working to a time limit, designers will settle on a familiar and satisfactory solution (Ball et al 1998) rather than instigate a prolonged analysis (Cross 1982) and may even be aiming for a final solution in the first attempt (Atkin 1992). This broad generalisation for design practice deserves further scrutiny to determine if on more evolved design projects this process of stereotyping is still followed.

More recent work on framing focuses on the interrogation of client briefs (Paton & Dorst 2011) as a method of clarifying a design commission shows that different stakeholders have their own perspectives of a brief and re-framing is used to form a common view. During the briefing process, designers confirm back to the client their opinions on the building by re-framing the brief to propose a solution that is realistic.

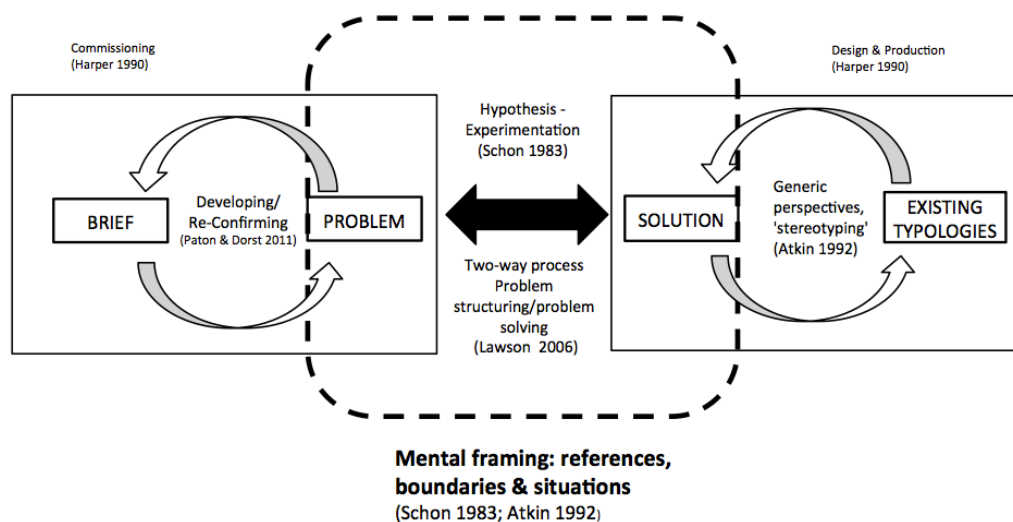


Figure 3: Framing of a design problem and solution

Figure 3 graphically summarises and collates the two current theories on framing activities for evaluating and reconfirming the brief (Paton & Dorst 2011) and framing of the solution with pre-existing typologies (Atkin 1992). The combined outcome of these two processes is a problem-structuring/problem-solving activity (Lawson 2006), defined through common boundaries (Schön 1983). Schön’s experimental process of hypothesising is a testing, rejecting and refining using this mental frame of the project design.

These processes are non-sequential: the process of confirming the problem through the brief, exploring existing typologies and refining the solution, occur in a loosely structured relationship as shown in this diagram. The research will test out this framing model and also look for the presence of linear and non-linear processes, which are known to occur. Under this model they are proposed as episodes of design activity occurring within the framing events.

3 RESEARCH METHODOLOGY

Epistemologically, the research is testing and revealing a condition that already exists and is therefore empirical realist in nature. The ontological position is predominantly objective, but recognises that organisational behaviour will influence this study and therefore is open to constructivist perspectives. The chosen research method for collecting and analysing this data is a case study approach (Yin 2008). Using a theoretical statement to enable an explanation or prediction of theory the approach is deductive, using linear techniques for analysis. However, as found in many studies, the distinction between inductive and deductive research is blurred as both approaches may occur during different stages of the same research process (Bryman & Bell 2007). Bryman & Bell propose a variant of the deductive empirical research model, which ends with an inductive phase: a hypothesis is deduced from literature and preliminary data and is scrutinized in the normal way to see if the main findings confirm or reject that initial hypothesis and, depending on the outcome of those research findings, the theory is further revised through an inductive process.

Data was collected from 25 interviews (40 hours) as part of a set of end-of-project 'After-Action' reviews (AAR) (Morrison & Meliza 1999), a hindsight process (Bartholomew 2005) intended to increase a group awareness of tacit knowledge. The team used memoranda and design models to communicate the design and these were interrogated along with project reports and drawings. The interviews were organised as structured conversations (Bryman 2007; Cresswell 2008) based around the topics of the AAR process.

Thematic analysis was used to extract data from the interview transcripts; a coding frame was developed for the analysis by:

1. Exploring themes and recurring topics, identifying repeated words and phrases
2. Sampling data from the interview transcripts based on descriptive statements referring to the design process
3. Sorting data under the key categories:
 - a. brief development/problem structuring (Patton & Dorst 2011)
 - b. problem solving/use of previous typologies (Atkin 1992),
 - c. framing of the problem and solution (Schön 1983; Lawson 2006)
4. Sorting this data under sub-categories:
 - a. analytical linear (*Pugh 1990; Cross 1990*)
 - b. conjectural non-linear (*Lawson 2006*)
5. Drawing inferences from connected quotes, repeated topics, and occurring phrases

The design team followed a prototype-design approach because of the scale of the station project (>2 billion USD) and its repetition of designs. The modularisation approach created a philosophy for the team of 150 architects and engineers to follow. The case study is treated here as a singular project because the four stations were developed simultaneously from an initial prototype design. Being a unique example of its type it has justified a singular detailed case study investigation (Yin 2008).

Figure 4 shows a typical section through the station platform and concourse. Although two of the stations were through-stations and two were arranged as terminus stations, they all had

common repeated elements: linear platforms and canopies of varying length and arrangement, based on a repeated modular design.

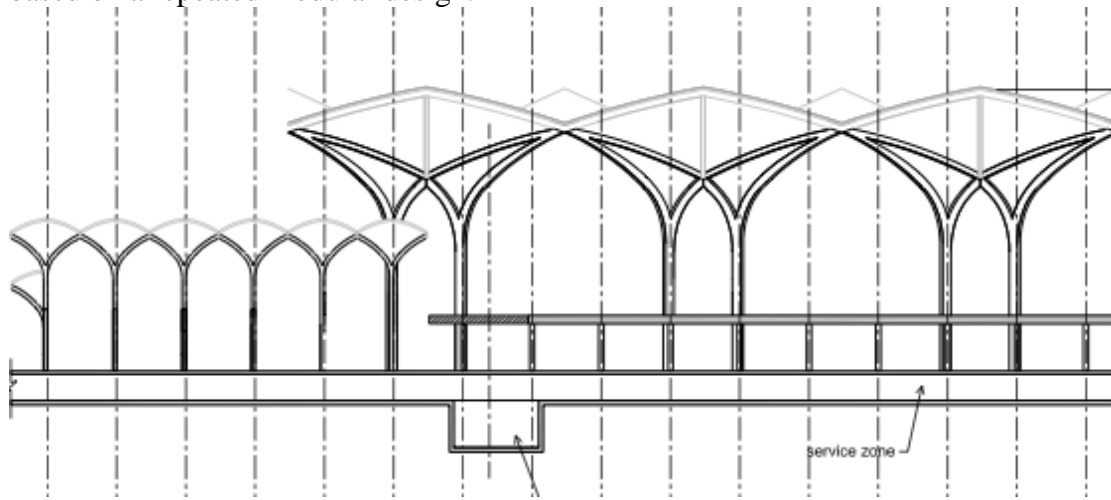


Figure 4: Typical cross section of similar building elements in stations.

The central concourse structures were of different scale, layout and number of levels, depending on their site and nature (terminus/through). The buildings had several other rationalised components and similar cladding treatments.

4 RESEARCH FINDINGS

The interrogation of drawings, reports and interviews was aimed at detecting the different strategies being used during the different phases of the project. The research findings are grouped under the three headings:

1. Brief development/problem structuring,
2. Problem solving/use of previous typologies,
3. Boundary framing of the problem and solution.

Brief development/problem structuring

Although the project started with the brief development, the observed evaluation/confirmation process continued throughout, including during the detailed design stages. Design outputs were presented to the client at each stage to reconfirm the way that the design was meeting the brief.

The client's brief was found to be under-developed; it contained a list of areas that the client would need for running and controlling the station, but there were no detailed requirements. "It describes what the entrance should encompass etc.... but (there are) no standards" (Designer O; 2010).

The design team created a document to re-state the brief back to the client. "Our objective was to convert the client's brief into a working document, as well as telling him what we were going to do" (Designer O; 2010). This document contained specific design criteria and design proposals. With the client only having a partially formed idea, the design team were taking on the role of 'expert/artist' (Paton & Dorst 2011), with the framing process being largely led by the design team.

The report shows evidence of a detailed analysis of the brief including a deliberation and selection of design options. The reports also conveyed design ideas: “we would add in design criteria and sketches to show him what systems we were using” (Designer O; 2010). The use of sketches suggests that these designs were preliminary and conjectural as to what the final proposal would contain. The designers were using their professional knowledge, including schemata and guiding principles (Patton & Dorst, 2011), to reframe the design problem.

Without full information on the operation of the railway, the JV appointed a sub-consultant as a proxy operator: “we all realised that we needed a rail operation specialist” (Design Manager AC; 2010). These separate consultants invented a virtual rail operation with a timetable, with generated passenger flows and station staffing levels in order to re-confirm assumptions about the size of the station concourse, platforms and accommodation. This process required both invention and detailed analytical processes to create the necessary data for understanding the design and operation. This situation confirms the need for a cyclical process of developing and re-confirming of the brief with the client (Paton & Dorst, 2011).

The client later appointed academics to assess the architecture. “The introduction of the professors post-concept, caused a delay to approvals as the design team needed to re-justify the design principles”. This indicates that a continuing process of deliberations and approvals was taking place during and beyond the brief definition phase. “...once on-board, their (professors’) subsequent endorsement of the scheme became useful later” (Architect AB; 2011). This shows that a building of relationships with the client body was helped through the framing process, and through the professors’ role the client team became more of a ‘collaborator’ with the architect (Paton & Dorst 2011).

Problem solving/use of previous typologies

For the layout of the public spaces and the architectural roof forms, the design team drew inspiration from their previous projects and airport buildings in particular. In the concept design documents, comparisons were made with repeating roof systems used in airport departure halls, as well as using local contextual references to forms such as arches and colonnades. Notwithstanding, there was little indication to suggest that design ‘stereotypes’ (Atkin 1992) were being used beyond the concept stage as idea generators. The airport precedents were closer to an initial framing technique using a primary generator for conjectural analysis (Patton & Dorst 2011). The options report detailed variations in repeating roof forms, with variations in pitch and grid spacing, showing a significant degree of analysis and synthesis with evaluation of these options. This process was “architect led”, being “really about what worked spatially and for operation” with the structural engineer “helping (the architect) to see what worked as a column grid” (Designer M; 2010). Therefore, the solution structuring process, which initially drew on other building typologies solutions, continued to be re-framed through a consideration of parameters (structural grid, jointing, vertical supports, optimisation of spanning structure) and within this process there were cycles of linear analytical design work.

However, the design team, led by the architects, operated a robust reviewing process called a design review board, occurring shortly before final design resolution at each stage in the project. As a result of these reviews, agreed detailed designs were frequently rejected, leading to re-designs.

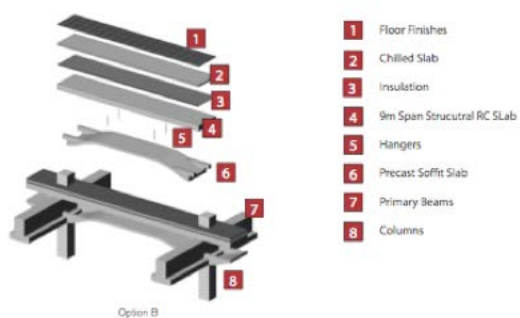
The timing of these was chosen to make sure that the design leadership endorsed the design presented to the client. The review boards were also helpful in identifying the critical issues for the design, giving the lead architect and his team fore-knowledge on which aspects of the scheme to push more strongly with the client, and which areas where they could show more flexibility. However, for many in the design team the results of these reviews appeared unpredictable and the process highly conjectural. In effect, some non-linearity seemed to be self-imposed through the architect's review processes. Major design revisions would be made at these reviews: “they decided to punch a hole all the way through, to connect to the platforms of the two through stations.... but we had a fire compartment between the station and the platforms (Designer P; 2010). Internal design meetings also had unpredictable results. The architect’s team “would change designs the day after the meeting where decisions were made” (Designer M; 2010). “The frustrating thing from our point of view was that we were committing to delivering Stage E and beginning of stage F” (Designer Q; 2010). Stage E & F are detailed design and contract production stages; these accounts show that conjectural design activity was occurring at the same time as more focussed linear and analytical processes associated with delivery of information.

Boundary framing of the problem and solution

The project was of sufficient scale to appoint senior designers to oversee each of the key disciplines; their role was separate to the delivery team in order to maintain an over-view of their own discipline. They were also required to be able to contextualise the technical requirements of their discipline from the overall project perspective. This became important for the design board, because discipline leaders needed to be able to “articulate a design concept or story” in negotiations with other disciplines. They also needed to have a clear picture of the overall context “making it clear why certain choices are made’ (Manager AF; 2010).

The use of design notes was also considered an “absolutely crucial tool” (Designer Q; 2010) for defining the design thinking and process for all the stations. These instances of technical oversight and communication are evidence that mental frames described through a set of boundary criteria (Schön 1989) were being defined to manage the detailed design of the buildings and the framing activity was instrumental in assisting collective team knowledge and understanding of the design problems being tackled (Atkin 1992).

For the concourse layouts, the prototyping team had developed a ‘kit of parts’ for the structural components (figure 5). Simplified analysis models were sent to the station teams,



who then worked them up into station specific models. The standard ‘kit of parts’ approach was also adopted for the drawings, with elements built-up piece by piece. This process was “tricky at the start, knowing where all the pieces went” and stations designers “needed to know design assumptions made for all the elements” but eventually it “became an incredibly fast tool” (Designer T; 2010).

Figure 5: Concourse ‘kit of parts’ structure

“The most efficient way of doing this was to design the stations simultaneously. When we ran models, the same person would look at the same part on the other station, applying learning from the first station straight away” (Designer T; 2010). This shows that the framing of design

problems was instrumental part of the evolved design solution using standardised components and sub-assembly designs.

5 CONCLUSIONS

To conclude that 'a structured design generation and synthesis is little practised by designers... and future designs are more likely to be combinations of previous designs...than representing a new line of thinking..' (Atkin 1992); p129, has not been evidenced in this study. The designers appeared to be using a structured approach to the design, they were synthesising problems associated with the brief, and developing original designs.

Reframing as a design theory is a convincing model for representing the overall process of design as shown in this case study; the design process is a non-sequential series of reflective mental activities grouped into loosely structured stages of briefing evaluation, solution testing and problem structuring/problem solving. The occurrence of each stage was interrelated with other stages; the brief process was negotiated, the testing out of building typologies was a conjectural and analytical process of testing and rejecting options, and the definition of framing boundaries for problem/solution was formally defined to become an important structure from which the detailed design emerged.

The modularisation process, based on an initial prototype was a predetermined strategy, in effect an evolved type of framing, with design parameters being defined through the prototype and then reconfirmed in the detailed design of the individual stations. Framing through modularisation as shown here is a productive technique for structuring and developing a standardised design.

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