EFFICIENCIES IN DESIGN AND MANUFACTURING FOR CONSTRUCTION USING SHIPPING CONTAINERS

Adrian Robinson[1], Simon Austin[2] and Alistair Gibb[3]

[1] *Buro Happold Consulting Engineers, 17 Newman Street, London W1T 1PD, UK.*
[2 3] *Dept. of Building and Civil Engineering, Loughborough University, Leicestershire, LE11 3TU, UK.*

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: containerisation, design, industrialisation, manufacturing, offsite, standardisation.

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 "ISBU's" (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).

[1] adrian.robinson@burohappold.com

Robinson, A, Austin, S and Gibb, A (2011) Efficiencies in design and manufacturing for construction using shipping containers *In:* Egbu, C. and Lou, E.C.W. (Eds.) *Procs 27th Annual ARCOM Conference*, 5-7 September 2011, Bristol, UK, Association of Researchers in Construction Management, 33-42.

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.

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 and Abley, 2004). Construction in the UK is characterised by low quality, high costs, a poor safety record, adversarial contracts, low investment in research and 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 and 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 and 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 'bulktainers', open-sided containers for pallet loading, rolling floor containers, 'swapbody' 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.

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) and **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; Keiran andTimberlake, 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 and 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 and Cockerham, 2001). The relationship between these products and types of preassembly is shown in figure 1 and later in Table 1.

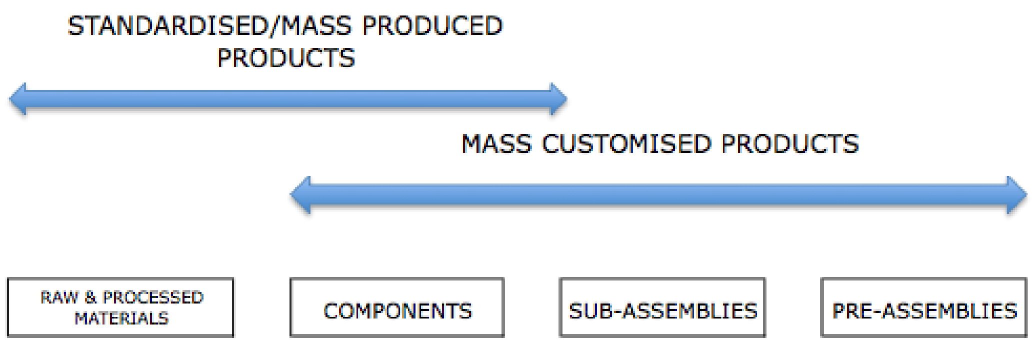

Figure 1: Ranges of Standardised and Customised products combined with levels of preassembly

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):

- Concept to Order (CtO): where the client initiates production at the start of information flow.
- Design to Order (DtO): where a basic product concept already exists, with a significant engineering design work done 'pre-bid' and 'post-contract'.
- 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.
- 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):

- Procurement, used in CtO strategies, where the information flow for project definition is separated from the detailed design and manufacture.
- Tender, used for DtO strategies, where the product concept is the customer's specification (employer's requirements).

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 and 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 Buidling
PRODUCTION STRATEGIES Winch (2003)	Concpt 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.

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 (ISBU's). The following questions were posed with the aim of understanding the characteristics of this form of construction:

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

RESEARCH DESIGN METHODS

The main approach for the research has been a literature search followed by interrogation of case study project data and 15 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 and 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. (Gilham, 2000).

PROJECT CASE STUDIES

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 ISBU's being shipped by container ship country to country and container trailer from port to site.

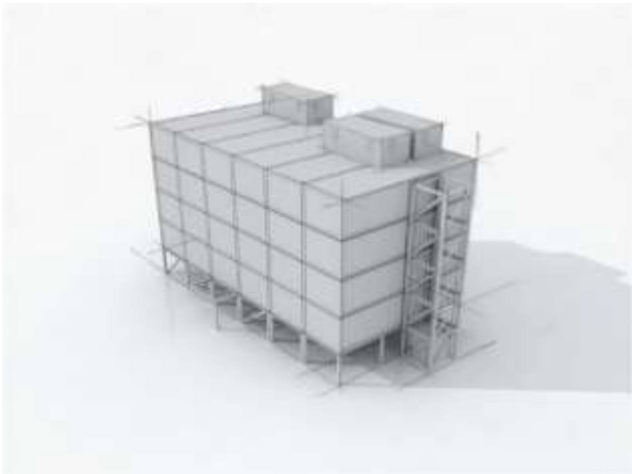

Figure 2: Generic general arrangement of containers with a steel frame ground floor structure and vertical risers

	Project details			Programme and contract	
Case Study	No. of Bedrooms	No. of Units	No. of Storeys	Construction Programme Duration	Procurement
A	181	86	8	14 months	Contractor led Design and Build Contract
B	310	181	7	11 months	
C	125	75	6	9 months	Manufacturer led supplier sub-contract
D	84	44	5	10 months	
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 ISBU's 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.

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 and risers, staircore, MandE services, roof structures)
- Modules (steel box and 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 and Cockerham, 2001) and production strategy (Winch, 2003).

PRODUCTION AND PROCESS STRATEGIES FOR CONTAINERS

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).

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.

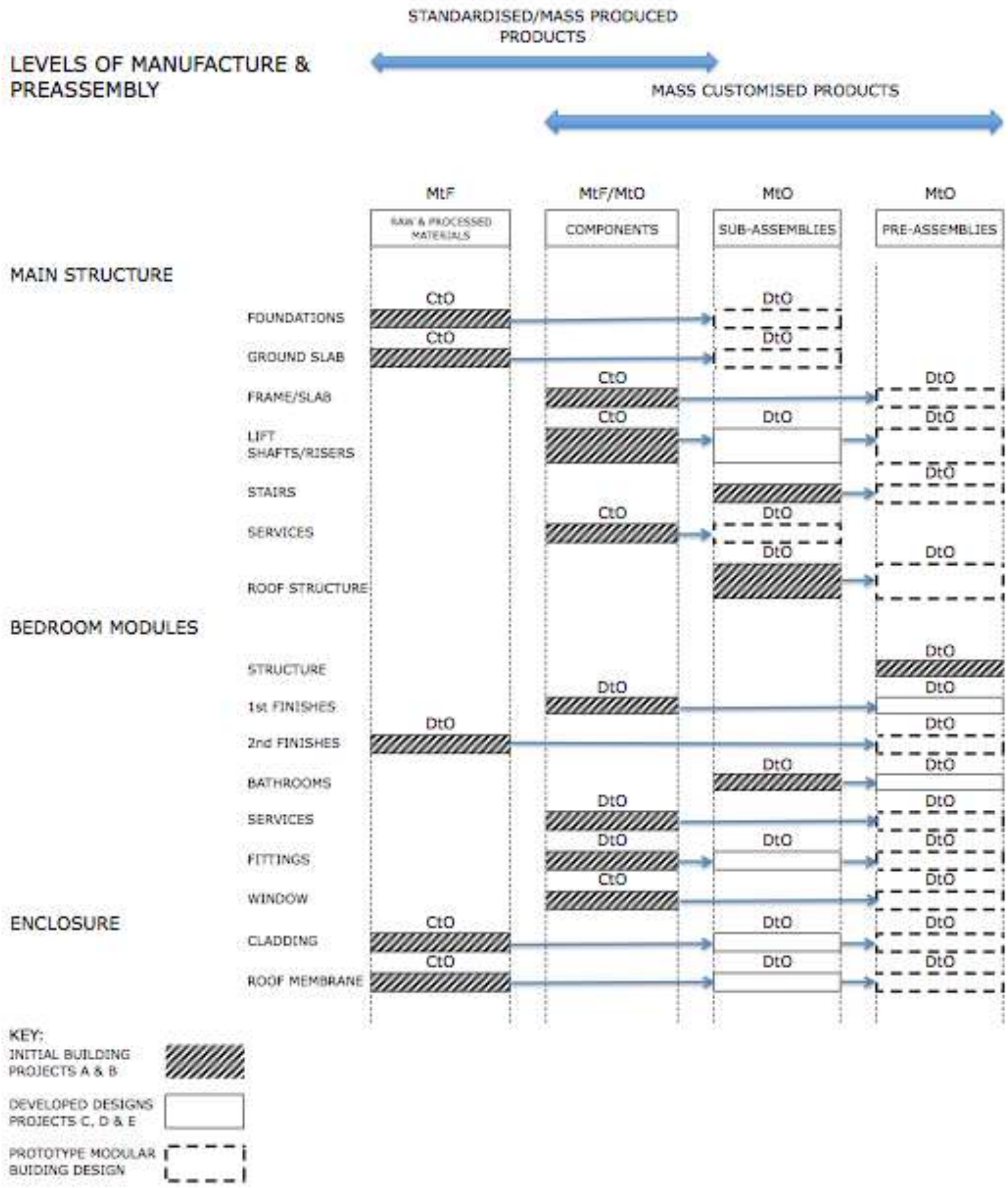

Figure 3: Development of preassembly levels for the different construction elements in a series of case study projects.

Process Strategies

Case study projects A and B were tendered as a Design and 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 and 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 and 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.

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.

CONCLUSIONS

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.

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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