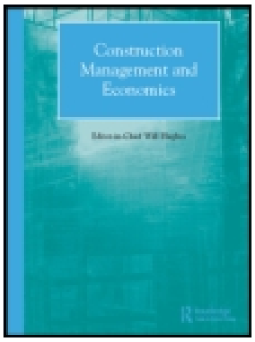

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Re-engineering the construction process in the speculative house-building sector

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The UK house-building industry has often been criticized for failing to meet the housing needs of the country. The traditional craft-based build process is labour intensive with a long lead-time and is difficult to control for product quality. It is also not suitable for configurable designs that would help to customize the home, and the industry has been criticized for excessive standardization of its products. Attempts at industrialization, usually employing frame or panel-based build methods seen in many countries, have failed due mainly to lack of clear objectives. A change in build technology is also only one step in addressing the concerns of poor quality and lack of product variety. The paper presents a programme of work that is being carried out with a major house builder towards re-engineering of the build process through a combination of new technology, product engineering and changes in working practices.

Keywords: House building, industrialized housing, process re-engineering, mass customization, supply chain management

Introduction

Among major industrialized countries, the UK invests one of the lowest shares of national income in housing (HBF, 1998). There has been a long-term decline in stock formation and replacement (Ball *et al.*, 1988; *Housing Finance*, 1998), but forecast demographic changes suggest the need for the reversal of this trend (DETR, 1997). The industry is dominated by builders whose business is characterized by the speculative purchase and development of land, and the building of a standard range of products for the single-family, owner-occupation market. The industry has been criticized for the poor quality of their products (Ball, 1996), and their excessive standardization does not cater for the diversity in demand that exists (Roy and Cochrane, 1999). There have been calls for a move from craft production to industrial build methods to address such concerns (e.g. Barlow, 1999). New build technology, using pre-fabricated structural components, is a first step, but changes in products and processes will also be required. The paper presents work that is being carried out with a major house-builder towards re-engineering of the build process for its efficiency, quality and capability to offer a wider range of products.

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Industrialization of house building

Speculative management of the land bank to profit from the dynamics of price inflation is the dominant business driver in the UK housing sector (Bramley *et al.*, 1995). Innovation in products and building processes has been of secondary importance (Barlow, 1999). Traditional brick-and-block masonry construction prevalent in England and Wales leads to a lengthy build process (about 17 weeks) and gives rise to inherent quality problems due to the use of 'wet trades'; a lengthy period of remedial work is common after occupancy. The industry has for many years tended to contract out the site work, reducing the role of the builder to that of managing groups of, often self-employed, craftsmen, which has made quality control difficult and has also been a factor in inhibiting innovation (Ball, 1996; Clarke and Wall, 1996). There

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have been many experiments with industrial build methods in the past, mainly in public housing (Finnimore, 1989). Pre-fabricated timber frames were even exported in the first half of the 19th century, and later corrugated iron, pre-cast concrete and steel were introduced for the provision of low-cost emergency homes. After the Second World War, there was a call for the use of mass production techniques. Eleven different pre-fabricated house types were built with public money, but none in sufficient volumes for capital costs in the factories to be amortized (Russel, 1981). The belief, pushed further in the 1960s, was that architecture was to be the instrument for social change (Russel, 1981). Miles (1996) attributed the failures to lack of clear objectives and the absence of major players in the industry from the experiments.

The only significant form of pre-fabricated houses in the UK currently is of timber-frame construction, accounting for 40% of homes built in Scotland in 1995 but only 3% in England and Wales (Mackay, 1996). Factory-build methods are more common in some European countries (Cooke and Walker, 1994; Gann, 1999), Japan (Bottom *et al.*, 1994; Gann, 1996), North America (Russell, 1991; Ryhn 1995) and elsewhere. Timber- and steel-frame are widely used in Japan and the USA. In Europe, examples of pre-fabrication methods include the Danish aerated concrete system (Ball *et al.*, 1988) and tunnel form concrete in the Netherlands (Ridout, 1989). Flexibility of the build process has also been the subject of studies on 'open building', which seek to separate the construction of the structure of the house from its fit-out (or 'infill') in a way that allows the latter to be easily personalized pre- and post-occupation (Ball *et al.*, 1988; Cuperus, 1994; Sawada, 1998). A review of trends in industrialized buildings can be found in Sarja (1998).

Ball (1996) has argued that industrialization of housing has not developed in the UK due to the absence of specialist sub-contractors. In Japan, for example, where the house buyer normally owns or acquires the land and commissions the building, it was a number of material processing and manufacturing firms that took the lead in creating a new housing industry (Gann, 1996). In the UK, however, the speculative land-acquisition process, a key business driver, and complexity of planning regulations are major barriers to new entrants. Instead, it is the builders who may have to be the agents for change and lead the future development of the industry by assuming the role of system integrators.

Drivers and model for change

The UK house-building industry faces no international competition, which has been the catalyst for change in many sectors. Housing is influenced by local culture and, Sawada (1998) suggests, is more likely to become 'internationalized' in a local context than take on a truly global character. However, a number of other drivers for industrialization are emerging in the UK. Masonry construction, although it provides good thermal stability, will struggle to meet increasingly stricter regulations on insulation standards (Ball, 1996). Skill shortage is a critical problem, partly due to a reduction in training places that resulted from the contracting out of site work by builders (Ball, 1996). Consumer affluence and experience with other industries are leading to expectation of better quality and greater choice of products (Cooke, 1996); a growing diversity of household formation is also likely to make greater product variety an imperative (DETR, 1997).

Dimensional integrity of the structural components is critical for product quality. The use of 'wet trades' in the traditional build method produces dimensional instability that adds to the inconsistencies of a craft-based process. This creates uncertainties also in follow-on processes for fitting out factory-made components (e.g. staircase) and skilled trades are often needed simply to overcome these problems. Quality is also affected by exposure to inclement weather and, hence, rapid assembly of the envelope is important. However, not all problems are related to the build method, but often arise from poor working practices and design of parts. Components need to be designed for ease of assembly if quality and efficiency is to be built into the production process (Boothroyd and Dewhurst, 1992).

Lean production (Womack and Jones, 1997) has been suggested as a model for addressing concerns of inefficiency and poor quality in construction (e.g. Alarcón, 1997). Many of its principles are widely applicable, but the model restricts variations in product mix and is not suitable if the aim is to personalize a large variety of products (Zipkin, 1991). An alternative model suggested for the housing sector (Barlow, 1999; Roy and Cochrane, 1999; Gann, 1999) is that of mass customization (Pine II, 1993; Kotha, 1995; Lampel and Mintzberg, 1996; Gilmore and Pine, 1997). It builds on the lean production model of eliminating wasteful use of resources by focusing on value creating processes and their outputs, instead of on individual functions as is common in craft and mass production (Womack and Jones, 1997), but also requires redesign of products and flexible/responsive processes to be able to offer greater choice for the mass market without the complexity of operations that would otherwise add to lead-times and cost.

Speculative builders in the UK offer customers a standard range of products based on architectural style and the number of bedrooms. Market segmentation is wide (two to six bedrooms) but shallow, with only a choice of internal fittings offered within each product. Complex planning procedures can take six months or more to reach agreement on the 'street scene' and, hence, the scope for customization is mainly limited to internal layout, configuration and fittings, but permutations of them can still produce a large choice of homes from the basic product range. Speed of order fulfilment will be important for mass customization, but it will also require 'open build' design and a flexible build process for late configuration of the product (Sarja, 1998). Modularity is important – for the process to be able to focus on key component systems, and for the product to enable easy interchange of components for product variety (Ulrich and Tung, 1991). There are also implications for many business processes, e.g. the design process has to be extended to include sales and service functions (Tseng *et al.*, 1996), modular designs for alternative functional uses of the living space will be needed for different market segments (Barlow, 1999; Roy and Cochrane, 1999), and the property may have to be described in terms of area of living space instead of by the number of bedrooms (Barlow, 1999).

The objective of the study was to consider how the build process can be re-engineered for quality, efficiency and responsiveness that will be needed to support mass customization of housing. The main focus is on the technology platform for the 'structure' to replace brick-and-block build, and on the 'infill' operations. Energy efficiency was an important consideration in the choice of platform, and reducing dependency on craft skills was an integral part of the methodology for re-engineering.

Selection of technology platform

For an initial assessment of build technology options, a multi-disciplinary team was put together of people from the Partner Company with technical knowledge and staff with site experience. Academic literature and technical brochures were also consulted. Team members were invited to assess individually the different options prior to an open debate to reach a consensual judgment. Although a degree of subjectivity cannot be ruled out, the approach made the process transparent. Comparison was based on *process criteria* that affect product quality and customization and process efficiency (primarily, speed of erection of a weatherproof shell, dimensional precision, compliance with open building concept) and *product performance criteria*, e.g. energy efficiency, acoustics and aesthetics. The aim was to select for build trials those options that did best against the process criteria and energy efficiency, and on others were at least of current/acceptable standards. Cost was not a prime consideration, other than that it had to be 'comparable' to that for traditional build. A description of the options considered is in Table 1 and the following are some of the main points that emerged from the team's deliberations.

- *Tunnel Form* (Ridout, 1989). The method requires a large number of products from each mould to make it cost effective (reported to be at least 60 by a supplier), which would seriously affect the aesthetics of the 'street scene' and it was not considered any further.
- *Volumetric Units* (Rhyn, 1995). The three-dimensional units are usually made of steel. The build method minimizes site work, but the factory space and, hence, investment cost for mass production of such sizeable units is high; the engineering specification needed for their transportation and safe lifting also adds to cost. However, shortage of site labour in the UK may tilt the cost equation in its favour in the future. They have been used in affordable housing in the US, but only for single-storey buildings (Lawson *et al.*, 1999). The structural steel work of the units also prevents open building approach (Gann, 1999).
- *Steel Frame* (Lawson *et al.*, 1999). Steel-frame build provides much of the benefits of industrialization without the higher costs of volumetric units, and is more flexible for wider ranges of customization (Gann, 1996). A potential problem for its acceptance in the UK, with its strong secondary market, is the lack of long-term performance data; in Japan, where it has been widely used, houses are usually rebuilt every 25–30 years (Gann, 1996).
- *Timber Frame* (Lyall, 1996). Timber-frame houses have longevity equivalent to that of masonry build, but minor concerns remain about the integrity of the vapour barrier and the differential movement between the frame and the brickwork (Covington *et al.*, 1995). The systems in the UK have a lower level of dimensional precision than steel-frames.
- *Gabeston* (Cooke and Walker, 1994). This aerated concrete panel system replaces the block work of a brick-and-block wall, and has comparable product performance, a relatively long build time and poor dimensional integrity. The floors, which are part of the system, do not have the span best suited for open build.
- *Foam-filled Structural Sandwich Panels*. This relatively new panel system, developed for commercial buildings, comes as sections of an inner skin with built-in insulation. The injected foam provides better sound attenuation than steel or timber frame, but not as good as for standard block work, Gabeston or KEPPS. Thermal insulation properties are very good, and a vapour barrier is not considered essential (Marshalls, 1996).
- *KEPPS*. This system is excellent for energy efficiency, but is expensive. The supplier recommends a rendered finish to save on the cost of brick cladding (Springvale, 1994), but the latter is

Table 1 Technology platform options considered

Masonry cavity wall	Standard brick and block method is the conventional form of house construction in England and Wales.
Tunnel form	A Dutch method in which concrete is poured over steel reinforcement and within a steel former, which is heated overnight and removed the next day providing the main structure for one or two houses (Ridout, 1989; Cooke and Walker, 1994).
Volumetric steel (pods)	Steel pods are prefabricated off-site and brought in by lorry. They are normally 80–100% finished inside. The system is widely used in Japanese housing (Bottom *et al.*, 1994). In the UK, it is primarily used for commercial projects such as hotel blocks and fast food outlets (Chevin, 1993).
Light gauge steel frame	This system produces a structural frame from cold rolled galvanized steel sections, which are made into panels that are bolted together on site (Lyall, 1996).
Timber frame	This system comes from the USA, where it is primarily stick built. In the UK, it comes as panels that are joined on site. It replaces the block work in a conventional house (Lyall, 1996).
Gasbeton	A Danish aerated concrete panel system. The panels are a storey high and 600 mm wide. They are jointed with adhesive and replace the block work in a conventional house (Cooke and Walker, 1994).
CPB/foam structural sandwich panels	A relatively new innovation in which the panels consist of two sheets of cement particleboard with an injected core of polyurethane foam. They are storey high and 1200 mm wide, set into a galvanized steel sole plate 'U' channel and are fixed together on site with cam locks or steel straps. They replace the block work in conventional houses (Marshalls, 1996).
KEPPS	A French system made up of polystyrene blocks in-filled with mass poured concrete (Springvale, 1994).
Hybrid timber-framed sandwich panels	A new innovation in which the storey-high panels consist of two sheets of facing boards with a core of timber frame and injected phenolic foam (Thermatech, 1998). The panel sizes were originally 1200 mm wide (or less), but were later changed to full (variable) wall lengths up to a maximum of 12 m. The facing material on the inside is plasterboard; the external facing material was changed from its original specification of plywood to cement particleboard.

Table 2 Rank order of different options produced by multi-disciplinary team

Platform option	Degree of pre-fabrication/ speed of construction	Dimensional precision/ minimum wastage	Aids open building	Energy efficiency	Comments
Volumetric	1	1	6	4	High investment cost
Steel frame	3	2	1	4	
Timber frame	4	6	1	4	
Gabeston	6	7	7	7	Good acoustics
KEPPS	7	4	8	1	Expensive
Structural panel	4	4	1	3	
Hybrid panel	2	2	1	2	
Brick and block	8	8	1	8	Good thermal stability

the preferred choice of house buyers in the UK (Roy and Cochrane, 1999).

- *Hybrid Timber-framed Sandwich Panels* (Thermatech, 1998). This was the only system considered that was not commercially available, providing the research team the opportunity to influence its development, e.g. size of the panels was changed to simplify the assembly process, from the standard 1200mm for panel systems into (variable) wall lengths (maximum of 12 m), and service conduits were added. The phenolic foam used in the system has excellent thermal insulation properties and it adds to the rigidity of the structure, making it less susceptible to movement than timber frame on its own.

There is little comparative literature available on technology platforms, and some of the options considered are new in the market. Table 2 summarizes the team's conclusions on their rank order in terms of the key criteria and, based on this, steel-frame and the two structural panel systems were selected for build trials. Except for the initial assessment of the hybrid panel system, which still had regulatory approval pending, houses were built for sale and under normal working conditions. The structural envelopes were built by their respective suppliers, and the process was critically observed to understand the potential of each method with respect to key process criteria, mainly speed of assembly. A standard two-storey, three-bedroom house design with a conventional gang nail truss roof was used in each case. For steel frame, the joists also must be in steel (Groak, 1992), but for the panel systems other options exist: timber joists, which are susceptible to shrinkage if exposed to the elements; concrete floors, which are expensive and lack flexibility for installation of services; composite 'I' beams, which have good all-round performance (Milner, 1996).

The first trial was with the structural sandwich panels, composite timber 'I' beam joists and steel stud partitions. A weather-tight shell was erected in six days by a three-man team from slab, compared to six to eight weeks it usually takes with masonry build. However, there was considerable scope for re-engineering the process. For example, placing the joists on top of the ground floor panels resulted in a need to fill the gaps between the joists with panel sections hand-cut on site; if the joists were hung, it could save three man-days of work.

The second trial was with steel-frame, steel internal walls and joists. A four-man crew erected the shell in five days. Again considerable scope for rationalization of the process was identified, e.g. in the floor design which required 1200 screws to fix the joists and the decking. Joists capable of spanning a longer distance would considerably reduce the time taken in building the first floor; there will also be fewer internal, load-bearing walls, which is important for open build. This and many other changes were incorporated in a second trial. It took four days for the shell, but if problems that arose with the new joist brackets were addressed, it is estimated this can be reduced to three days.

The initial trial with the hybrid timber-framed sandwich panels was the only one carried out off-site. Timber joists were used, and a non-load-bearing version of the panels, with foam injected between sheets of plasterboards, was also tried for internal walls. The elements of the envelope were craned into position by a five-man team in two half-days, with a break in-between due to severe weather conditions; later on-site trials confirmed completion within a day for the standard three-bedroom house (and under two days for all house types). The change to wall-length panels was a significant factor in making the process efficient by reducing the number of components and ensuring dimensional integrity of the whole wall as a unit. The internal partitions proved to be a disappointment; although they had greater solidity than walls built using conventional dry lining techniques, tests showed inadequate sound absorption and timber stud partitions were later adopted.

The houses were tested for acoustics, air tightness and energy efficiency. The results are confidential, but all showed similar or improved performance compared to that for houses built using conventional methods. A recent industry survey suggests increasing public awareness in the UK of the benefits of homes built using new construction methods, but some marketing effort may be needed to overcome scepticism that still remains (NHMB and Halifax, 2001). Builders will also have to learn from past mistakes, e.g. an attempt at introducing timber-frame homes in 1980s is believed to have failed due to poor on-site working practices (Gann and Senker, 1993). The trials also showed considerable scope for re-engineering each of the build methods to maximize the benefits of industrialization.

Steel-frame is widely used in many countries, but a pre-insulated, dry lined panel system provides a more complete alternative solution and reduces the need for craft skills later. The hybrid system with its wall-sized panels did best on the important process criteria, as is evident from the fast time to assemble the envelope, and also scored very well on air tightness, fire resistance properties and energy efficiency. In a market in which the supply base is still small and relatively unsophisticated, the ability to influence its future development was also seen as an advantage. It will be produced in the future in a new factory by a subsidiary of the Partner Company, along with timber stud partitions and an I-beam cassette-floor system. The development of a roof system based on the same process as for the structural walls remains an option – the concept is similar to the Dutch purlin roof that also places insulation in a structural panel (Cooke and Walker, 1994).

Re-engineering the construction process

Figure 1 shows the new process. The total build time is reduced to six to eight weeks, the time to erect the structural envelope to one to two days, and inherent quality problems of 'wet' processes are removed. The built-in service channels and the dimensional precision of the walls also provide a good platform to simplify the infill operations, which is in part a 'fitting' process. Product engineering is usually needed to change such a process into one of assembly of engineered parts for quality and efficiency of production. Principles of design for assembly (DFA) are well established (Boothroyd and Dewhurst, 1992) and the concept of design for construction is also not new (Fox, 1988). DFA, however, aims for a reduction in parts count and may lead to integral designs, but for modularity, the emphasis is usually on redesign of interfaces between components (Meyer and Lehnerd, 1997).

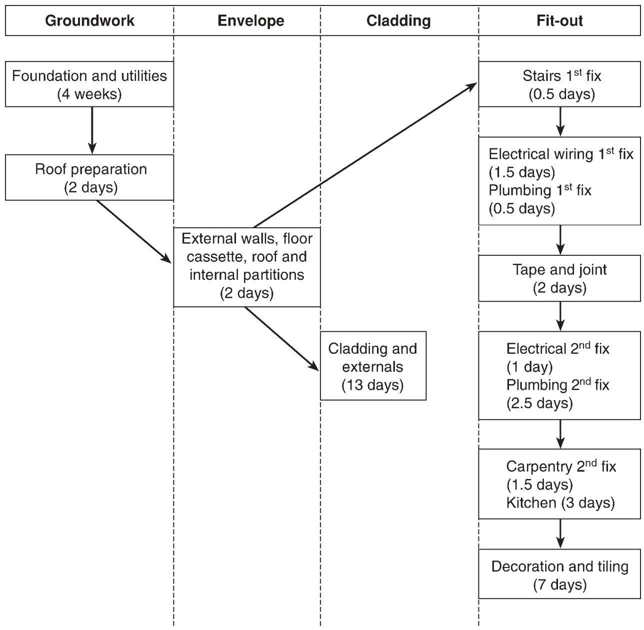

Figure 1 Outline of the new build process

Installation of sanitary wares

Faulty connections in sanitary wares are major sources of defects in new homes. A project with a sanitary ware manufacturer has produced prototypes of pre-plumbed bath, washbasin and WC for push-fit connection to the pipe work; the taps and washers are factory-fitted, and the flush mechanism for the WC tested for water volume and leaks by the manufacturer. The bath has been redesigned to be simply lowered on to the waste outlet for connection, with its weight helping to form the seal; the pipe work is to be designed for factory-installation within the cassette floor. A plumber will then only be needed for the external connections. In an off-site trial, the units for a complete bathroom were fitted in 15 minutes.

Space and water heating unit

A similar proposal for push-fit connection has been developed by a manufacturer of boiler units, but no prototypes have yet been produced. Another interesting idea that is being developed is to design the boiler in small modules that can be assembled or disassembled easily for customization pre- or post-occupation.

Electrical wiring

The factory-built walls have conduits for electrical wires. Initial trials showed the need for slight changes to the design of the house for easier access to the conduits. With the use of pre-cut cables, coded by applications for easy recognition, the task of threading them should not require a skilled electrician. A manufacturer of electrical control equipment has also produced designs for new switch and socket covers for push-fit connection to 'back boxes' that can be fitted in the factory to the wall panels. This will eliminate the need for an electrician except for safety-critical work.

Internal doors

A kit of parts has been developed by a supplier for rapid assembly of doors with minimum requirement for carpentry skills. The door lining is assembled in the factory; the door, frame and the architrave on one side are fitted on site with mechanical fixings, and the final piece of architrave is then glued into place. Dimensional adjustments are often necessary but, with the precision components of the new technology platform, should not be needed in the future and slide clips will replace the mechanical fixings. It will also remove the need for remedial work that is currently required to conceal the fixings, and is expected to reduce the assembly time to 35 minutes.

Windows and external doors

Windows and external doors are to be fitted in the factory. A new window design incorporates an acceptor to allow for cavity closure on site and 'snap-on' cills, which prevent damage during transit.

The potential reductions in time for the individual assembly tasks are significant, but their impact on the infill time will depend on how effectively the process is managed and reliability of material supply. The more direct benefit will be the effect on quality and flexibility of build, and in reducing or eliminating dependence on a number of trades. The use of poorly trained, often self-employed, sub-contract labour is also an obstacle to quality control (Ball, 1996; Clarke and Wall, 1996). The way work/contracts are organized around trade groups exacerbates the problem; there is a lack of focus on the product and its sub-systems and no clear accountability for their quality. The problem is particularly critical in the finishing stages of the build process. A large proportion of customer complaints consistently arise from damages to paint finish, work surfaces and other similar defects. Pilot use of multi-skilled teams, trained and directly employed by the Partner Company for 2nd fix carpentry, decoration, assembly of door furniture and sanitary ware fittings, etc so far indicates 50% drop in recorded defects. By reducing the levels of skills necessary for the many assembly tasks, it should become possible for the builders to develop multi-skilled teams to take responsibility for the whole infill process, with minimal input from sub-contractors. Tiling, and tape-and-joint are two functions that will still require high levels of skill, which will have to be incorporated in the multi-skilled teams, or external input will be needed in these two defined areas.

Focus on value creating processes is the basis for re-engineering as a tool (Hammer and Champy, 1993), and integral to lean production and part of the mass customization model. Instead of the current focus on functional trade groups, the builder should look to divide the build process into the production of a small number of key 'modules', with a team accountable in each case for completing it to measurable quality standards. There are four main value creating processes: *foundation* – pre-cast concrete foundation is expensive, but alternative methods are worth investigating to simplify a process that is prone to errors and time consuming; *envelope* – the structural envelope as a whole (completed walls, roof, floors) should be treated as an assembly module, with a lead supplier/module integrator responsible for its rapid installation; *infill* – for quality control and efficient customization to individual orders, it is important that the multi-skilled team is employed by the builder; *cladding* – traditional look of hand-laid brick cladding is popular in the UK (Roy and Cochrane, 1999) but, if market preference changes, factory-fitted brick slips or brick panels are other options that will eliminate or further reduce need for bricklayers.

A change from a sequential process to modular build also simplifies its planning and control. The structure and infill have different imperatives. The envelopes, requiring only one to two days to erect, are best built in batches (speculatively) for efficient use of the assembly team; its build will need to be closely co-ordinated with the foundation to avoid the inefficiencies that occur when the latter is not ready on time; one possibility is to treat the foundation (excluding ground preparation) as part of the same module for assembly of the structure. The interior has to be customized to order; internals walls will have to be installed in the infill stage if choice of room configuration is to be offered. Cladding, which is not part of the structure anymore, can be planned as a separate process.

Inefficiency and quality problems also result from poor working practices and lack of attention to process details (Womack and Jones, 1997). In the house-building industry, there is a lack of any process documentation and standards, or formal mechanisms for sharing knowledge and good practices. The development and use of formal process sheets by site staff for training the 'finishing' teams showed their value – the resulting drive towards standardization became a catalyst for examination of working practices that affect process quality. Clearly, it is impossible to separate out the effects of the new working arrangements from that of the process thinking that went into structuring the work but, as indicated earlier, results show 50% drop in defects.

Implications for component supply

Production quality, efficiency and flexibility also depend on supply chain logistics (Macbeth and Ferguson, 1994; Womack and Jones, 1994). In the house-building industry, for example, late delivery of parts often lead to inefficient use of labour or time pressure on following operations that may affect product quality. A reliable and responsive supply chain with short lead-times will also be essential for an efficient, customized infill.

The builder will have to improve its own logistics management capability. An example of this was seen in a study of the operations of a supplier of staircases. Late deliveries and supply of incorrect parts were common complaints levied against it that, in turn, pointed to the late receipt and poor quality of information (e.g. incomplete specification) from the building sites as the source of the problem. Poor communication is a common feature of the industry, partly due to limited administrative support on site. The specification data, however, are in build programmes available in regional offices. The exception is the floor height since deviation from specification can be significant with brick-and-block build. A simple procedure has been piloted. The build programme is sent to the supplier for specification data, and weekly build progress reports are sent to indicate the supply schedule. When a defined trigger point is reached, staff/contractor on site confirms the order with the floor height in a telephone/fax message. In trials running for several months, the supply problems have been virtually eliminated. Such information sharing and the integration of systems will be essential for rapid translation of customer choices into materials requirement for efficient customization (Bottom *et al.*, 1996; Gann, 1996).

The same supplier's operations also illustrate the typical problem with lead-times. Its delivery lead-time is three weeks although the longest chain in the manufacturing route has a total process time of only 3 hours and 45 minutes. One week is allowed for obtaining any missing specification data, and two weeks for production and transportation. The practice of working to weekly planning buckets is clearly not compatible with mass customization. The problem of missing data has been addressed previously. Methodologies for reduction of production lead-time using cellular/ lean manufacturing principles are well documented (Schoenberger, 1986; Ohno, 1988; Womack and Jones, 1997). Transportation is a problem since the supplier works to a weekly rota for delivery to different regions, and the cost of using more flexible carriers will need to be investigated. More generally, the builder may need to take an active role in the organization of logistics on behalf of its supply chain; similar trends can be seen in the automotive industry.

Conclusion

The UK housing industry has been criticized for falling behind its counterparts in other countries in innovation, and for failing its customers with poor quality and limited range of products (Ball, 1998). Increasingly stringent regulation on energy efficiency is prompting builders to investigate alternative build technologies. Although it will address some of the inherent weaknesses of brick-and-block construction, this alone will not produce all the changes necessary for the emergence of a customer-focused industry. Mass customization provides a conceptual model for the speculative builder if it is to offer a large variety of products in an efficient manner and improve product quality. Table 3 summarizes some of the key steps that will be necessary. Modular designs of the living space aimed at different segments of the market (e.g. empty nesters, home workers) will have to be supported by a build process designed for efficiency, quality and flexibility/responsiveness. Any new technology has to be adopted and used as a platform to achieve these aims. The current process is sequential, craft-based and organized around a network of trade groups, with management focus on individual functions than on the key product modules that create value. It has to change to an efficient, modular industrial process with teams focused on the quality of product modules and rapid customization of the home.

The structure is a technology-based module, which needs to be designed for the efficiency and quality of the manufacture of its parts, their on-site assembly and the subsequent in-fill process. A sophisticated module integrator will be needed to take responsibility for its development, design, supply and installation to a completed state ready for customized infill when an order is placed for the property. The aesthetic value placed on hand-laid brick cladding restricts industrialization in this area but, not being part of a structural element anymore, it has a considerably reduced effect on the overall build time and quality. As a single-skill process, the module may continue to be built on a sub-contract labour model; however, the builder should seek to involve the brick suppliers in improving the process that uses their products. The infill module, with its dependence on a large number of trade groups, is where lack of focus on the process is most evident. Innovative product engineering can change the 'fitting' tasks into assembly of engineered components in a factory or on site for build quality. It can also considerably reduce dependence on craft skills, which will be necessary to develop multi-skilled teams, employed and trained by the builder for quality control and efficient customization. However, the process needs to be reviewed to develop 'best practice' standards if the teams are not to repeat current working practices and become ineffective.

The supply of components is currently not reliable or responsive enough for an efficient process for customization of the infill. If supply chain performance is to improve, the adversarial relationship prevalent in the industry has to be replaced by a partnership culture (Ball, 1996). Partnering should not become a tool for 'management by objective', but used to analyse the bottlenecks in the supply chain processes and put in place improvement programmes (Maskell, 1991; Bennett and Jayes, 1995; Barlow *et al.*, 1997). Some suppliers may benefit from direct assistance to improve the internal capability of their processes; this is an important role of system integrators (Lamming, 1993).

Implications of the changes are considerable. The builder has to examine its own core competencies, which are traditionally in land acquisition, sales and site-development. System integration for industrialized housing and mass customization will involve design for modularity and efficiency of assembly, process engineering and efficient supply chain management. In time, specialist firms may emerge (from within or outside the sector) to take on some of that role in developing a new industry. This has happened to an extent in Japan, where

Table 3 Re-engineering for mass customization of housing

Key features	Traditional house builder	Mass customization model
Product design	Integrated; limited choice of fittings; shallow market segmentation	Modular design of interior aimed at different market segments; customer input into design of end product
Product engineering	Components designed individually	Engineered for efficient and modular assembly; minimize requirement of craft skills
Build process	Construction/fitting; sequential; lack of process standards	Assembly of pre-fabricated parts; modular planning and build; 'best practice' process standards
Teams	Organized around trades; single-skilled	Organized around key product modules; multi-skilled
Business processes	Fragmented, functionally organized	Integrated for rapid response
Supply chain	Adversarial relationship; fragmented	Partnership for product/process innovation; improved communication; co-ordinated material flow
Culture	Tolerant of failures	Continuous improvement
Role of builder	Prime contractor	System integrator, innovation leader/co-ordinator

manufacturers from outside the sector have become major house builders, employing traditional contractors for site work and providing high quality customized homes (Gann, 1996), although their production costs and target market sectors compared to the house builders serving the mass market in the UK is not clear. The relationship may develop differently in the UK if house building continues to be based on the speculative development of land due to the concentration of its ownership. The builder, with its land bank and knowledge of the complex planning regulations, may instead engage the services of specialist firms to create a new efficient supply chain for its products.

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