DEVELOPING TEMPORARY MANUFACTURING FACILITIES FOR RESIDENTIAL BUILDING: A CASE OF THE MODERN FLYING FACTORY

Bert Young[1]**, Chris Harty, Shu-Ling Lu and Richard Davies**

School of Construction Management and Engineering, University of Reading, Reading, UK

The building industry is often berated for its short comings in meeting up with the demand for the provision of new housing. Addressing the need for new housing stock is a challenge that has led to debates among professional bodies, the construction sector, housing industry and government. The introduction of new manufacturing technologies is often offered as a solution, but the challenges of increasing the amount of off-site construction in residential building are well known and well-rehearsed. The modern flying factory (MFF) is a concept that involves the manufacture of specific components or modules in temporary off- or near- site locations using relatively simple and quick to set up and dismantle technologies and processes. The aim is to produce short batches and hence achieve some of the benefits of off-site manufacture on a much smaller scale than in dedicated factory environments. A case study of a modern flying factory being set up to produce pre-assembled utility cupboards for a large residential development in London is presented, involving participant observation and informal interviews with key actors on the design and operationalising of the process. The case reveals that although there are costs, efficiency and health and safety benefits to using MFF approaches, there are also challenges to overcome over the time required to set up and establish the process for relatively short runs, and in evaluating whether the MFF or traditional site based production is most effective for particular aspects of projects.

Keywords: manufacturing, house building, flying factory.

INTRODUCTION

The topic of off-site, industrialised building or Modern Methods of Construction is one which has been debated considerably in construction. Work by scholars such as Gibb (1999), Goodier and Gibb (2007), Pan *et al* (2007) and many others have both rehearsed the benefits of off-site manufacture, and commented on the modest uptake of such processes in a UK context. Reduction of time and amount of activities on site (along with the health and safety advantages a factory environment brings) and improved quality are often cited as the benefits. But these are tensioned against issues such as the initial investments and economies of scale required (Boyd, 2012), the relative inflexibility of modular components versus bespoke design (Lawson, 2014) and a general perception that modular construction is more expensive than traditional are three of the main reasons given for this, even if some increase in use, especially in housing, has been found (Goodier and Gibb, 2007).

Alongside this is a growing problem in meeting demand for new housing, with the estimated 115,000 new homes per year being produced falling some way short of the

[1] b.e.young@pgr.reading.ac.uk

Young, B, Harty, C, Lu, S-L and Davies, R (2015) Developing temporary manufacturing facilities for residential building: A case of the modern flying factory *In:* Raidén, A B and Aboagye-Nimo, E (Eds) *Procs 31st Annual ARCOM Conference,* 7-9 September 2015, Lincoln, UK, Association of Researchers in Construction Management, 1033-1042.

estimated requirement of 260,000. There are an estimated 2.6 million 'concealed households' in the UK - defined as separately identifiable family units but which do not have separate facilities. The scale of the problem is continually growing with an increasing population and growing gap between supply and demand. Increasing the use and scale of off-site manufacture is heralded as one solution to address this, but despite its benefits, this remains a significant challenge.

This paper describes a case study piloting a form of off-site manufacture which realises some of the benefits of off-site but at a smaller scale, with more flexible and temporary facilities - the Modern Flying Factory. It is part of a Technology Strategy Board funded project led by Skanska UK, one of the UK's largest contracting organisations. Specifically, this case concerns the development and production of utility cupboards - pre-assembled units containing the electricity switch board, boiler, washing machine and related services which can be then installed on site in one go. The housing project is a large residential development in south London. The aim of the paper is to report on the instigation and development of this modern flying factory, and to shed light on the practical challenges that emerge from this process.

MODERN METHODS OF CONSTRUCTION (MMC)

There are a number of related and interconnected terms used to describe the production of building components or sections away from the building site. Pan *et al* (2007) describes how early discussions of 'prefabrication' have moved through 'off-site fabrication' to 'off-site manufacture' and most recently MMC. Although there are important variations in terms of types of MMC (for instance component or volumetric) for consistency we use MMC in this discussion.

Despite the attractiveness of offsite technologies, in term of process benefits and economic impact, both the nature and the scale of innovation in the UK house building sector are conservative in comparison with other countries (Hooper, 1998). The Barker report (Barker, 2004) specifically identifies increasing the use of off-site and addressing the barriers to the take up of MMC as vital to addressing the UK's housing shortage.

Modern Methods of Construction (MMC) as defined by Gibb (1999) is a process that incorporates prefabrication and pre-assembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the building site. It is a project strategy that promises to change the orientation of the building process from construction to manufacture and installation. Benefits from using such technologies have been widely studied by (Gibb, 1999; Sparksman *et al*., 1999; Housing Forum, 2002; Parry *et al*., 2003; Venables *et al*., 2004) and they include reductions in cost, time, defects, health and safety risks, environmental impact and a consequent increase in predictability, whole life performance and profits. MMC are:

"about better products and processes. They aim to improve business efficiency, quality, customer satisfaction, environmental performance, sustainability and the predictability of delivery timescales. Modern Methods of Construction are, therefore, more broadly based than a particular focus on product. They engage people to seek improvement, through better processes, in the delivery and performance of construction." (Barker 33 Cross-Industry Group, 2006).

What makes MMC *"more broadly based"* than just prefabrication is the application of 'new production philosophies': an evolving set of methodologies, techniques and tools, the genesis of which was in the Japanese JIT and TQC efforts in car manufacturing that have since been applied to construction (Koskela 1992). The core of the new production philosophy is in the recognition of two distinct aspects of all production systems; (a) conversions; value adding activities and (b) flow; non-value adding activities; inspection, waiting, moving etc. (Koskela, 1997). Managing these activities (by optimising conversions and eliminating flow) can contribute to significant improvements in construction processes in modular housebuilding as measured by cost, time and sustainability indicators (Nahmens and Ikuma, 2011).

THE MODERN FLYING FACTORY

The concept of the Modern Flying Factory (MFF) is positioned somewhere between full scale, permanent manufacturing facilities and traditional site based construction. It involves the use of a temporary, near site facility, which is used to manufacture or assemble components using relatively low-tech equipment, which are then taken to site. The first pilot for the project involved the manufacture of straw bale wall panels in a farm building for an extension to a school in Bristol which took place in the summer of 2013. The advantages of the MFF compared to a fixed prefabrication assembly are flexible short term leases on the space, low capital intensity in the production system, minimising transportation of volumetric components (and related energy reduction benefits), and the use of local materials and, where possible, labour. The main aim is to deliver the benefits of off-site factory assembly whilst overcoming the barriers of high capital investment and high transport costs. Skanska UK estimate this approach has the potential to deliver 30% shorter programmes, a 28% reduction in cost per square metre (as well as a more predictable build cost) and provide higher-quality. This is because the structure is built in controlled conditions, removing the potential effects of bad weather and other on-site hazards, and speeding up the assembly of the building on site.

The MFF is similar in concept to Martinez *et al* (2013) 'flexible field factory' which seeks to addresses the same niche in the construction production system but via a mobile automated assembly plant based on a shipping container. The difference between flexible field factory and MFF is that the former is oriented towards frequently repeated tasks and proposes a relatively high degree of capital-intensive automation for that task on the assumption that sufficient high-volume projects would be available to move the field factory between. It is also implicit that the field factory would be deployed on-site. MFF is a more open system potentially applicable to any components or sub-assemblies except those that require significant capital investment.

The project-specific nature of MFF puts it within the analytical scope of Gann and Salter's (2000) project-based project framework in which the MFF can be seen as an integrator within a network, mediating between material and component suppliers and the construction site. The project-specific MFF is likely therefore to share many of the characteristics of construction project organising that have been shown to be challenging to the adoption of lean manufacturing concepts in general (Vrijhoef and Koskela, 2005) and for industrialised housing in particular (Höök and Stehn, 2008). For instance, in Höök and Stehn's (2008) research, construction workers in an industrialised housing production system had low motivation to consider built-in quality, continuous improvement and consideration of flow which was attributed to the prevalent construction project culture.

The fact that the MFF is embedded within a 'loosely coupled' (Dubois and Gadde, 2002) production system defined by a construction project presents both 'upstream' and 'downstream' challenges. For example, by removing some elements of on-site work the overall project process will require some reconfiguration or re-sequencing. Conversely, the typical project processes in which work packages are often awarded close to construction might limit the amount of pre-planning and optimisation of the specific MFF. The case study and analysis follows the set-up and operation of the MFF in order to investigate these challenges in a real environment.

METHOD

In line with calls for more connectivity between academic research and practice (e.g. Green and Harty, 2008; Stokes and Dainty, 2011) this case study involves collaborative co-production of both activities and data in a live setting. The research design is a longitudinal single case study overlapping with an ongoing action research programme (Brydon-Miller *et al*, 2003). The action research project consortium is led by Skanska UK and involves Modcell, the South West Manufacturing Advisory Service, the Building Research Establishment and the University of Reading. The findings reported here were developed primarily through the single case study. In that study the researcher spent time at the MFF during its set-up and during the manufacture of the utility cupboards. Non-participant observation of work processes, and the physical setting and products of the factory were supplemented by ongoing discussions and informal interviews with factory managers and staff and members of the action research team. Additionally the researcher performed a form of cross-case participant observation assisting action research team members with work study and also attended action research programme meetings and discussions. Overall, the case represents a detailed and finely grained account of the efforts involved in mobilising the modern flying factory.

CASE DESCRIPTION

Before Skanska UK set up the MFF, the project consortium established the following criteria for the delivery of the MFF and the utility cupboards: (1) the location for the MFF must be no more than a distance of 20-25 miles radius from the residential development in order to achieve the full potential of the off-site construction facility; (2) the utility cupboard must be fit for purpose; (3) there must be strict adherence to sustainability requirements; (4) it must be economical and being able to reduce the construction programme time for the project; (5) the MFF must produce reductions in carbon dioxide emissions; (6) the setup and operation of the MFF must be achieved at a reasonable cost; and, (7) the MFF must be able to contribute directly or indirectly to the resolution of the UK housing shortage.

A total number of 855 utility cupboards are required for the residential development's first phase - 535 units to be constructed in the factory and 320 units to be constructed in-situ. The need for in-situ construction is due to variation in the spaces available in some of the apartments in the development. It was anticipated at the start of the built-out (in the second quarter of 2014) that the MFF at full production capacity would produce 20 units per week.

Process of the start-up and operation of modern flying factory (MFF)

The initial findings identify two phases of set-up and operation. Each phase is described below.

Phase 1: Set up of the modern flying factory (MFF)

This first phase was to set up the MFF. The choice of a factory location / space was a warehouse space adjacent to the builder's off-site manufacturing factory in Slough. Further, the factory was located within 25 miles of the housing development site. The proximity to the residential development site would reduce the cost of transportation and also have a significant reduction in carbon dioxide emission from the trucks that would be involved with transporting the final products (the utility cupboard) to the construction site (an important sustainability factor).

Phase 2: Manufacturing / production of the utility cupboards

The second phase, the manufacturing / production of the utility cupboards consisted of two stages: constructing the cupboard, and installation and construction of the internal fixtures. Each stage is discussed in detail below.

1. Constructing the cupboard
The construction of the cupboard can be divided into six stages, including delivery of the metal frames to the factory (activity 1-1), fixing of boarding to the back of the metal frames (activity 1-2), boarding to the top and sides of metal frame (activity 1-3), plaster boarding (activity 4), plaster board fix to the front edges at the top and sides of the cupboard (activity 1-5), and taping and plastering of the cupboard (activity 1-6). Finally, a completed cupboard ready for the installation and construction of the internal fixtures.

2. Installation and construction of the internal fixtures
The installation and construction of the internal fixtures consisted of five sub-processes: fixing the electrical conduits (activity 2-1), installation of the water retainer and distributor with heat exchanger (HIU Unit) (activity 2-2), installation of the water pipes for the cold and hot water system (activity 2-3), fixing of the electrical switch board, electrical units and sockets, and heat reclamation unit (MVHR) to enable electrical installations (activity 2-4); and installation of telephone box, satellite box and the TV cable points (activity 2-5). Finally, a completed utility cupboard in the factory is ready for transportation to the site.

INTERIM FINDINGS

Key challenges of the set-up and operation of modern flying factory (MFF)

The initial findings indicate that there are a number of challenges to the setup of a modern flying factory (MFF) and the manufacturing / production process subsystems such as utility cupboards. These are less to do with internal processes within the factory itself, but more the interdependence between the MFF, supply chain and wider project activities. These key challenges are discussed in more detail below.

1. Material procurements to specification
Acquisition of materials and components to specification for utilisation in constructing the utility cupboards caused a number of specific problems as specification details were not adhered to by manufacturers and suppliers. The non-compliance to specification led to the following problems encountered during the manufacturing process.

First, the metal frames supplied for starting the process were painted in 'black' instead of the specified grey colour (activity 1-1). The rework of repainting the metal frame in black incurred extra person hours and led to a slow-down of the production speed. A further planned improvement is to move from metal to wooden frames which do not require painting. Second, four 12 mm diameter holes at the base of the supplied metal frames were incorporated into the design to be used as the stabiliser and also to create space between the metal frame and the concrete floor during assembly (activity 1-3). These holes were either not in place, or they were incorrectly placed requiring rework and adaption.

Third, the pre-drilled holes in the plywood boards supplied for the top of the cupboard were not correctly placed for installing pipes for the water retainer and distributor with heat exchanger (HIU unit) (activities 2-2 and 2-3) and the vents for the heat reclamation unit (MVHR unit) (activity 2-4). Finally, the plaster boards used were initially not cut to the correct dimensions. This occurred as a result of an error from the initial drawings and specification obtained from the consultants who did not take into consideration the thickness of the plywood board at the back of the cupboard would extend into the internal part of the metal frame. This thickness should have been deducted from the width of the plaster board during the initial drawings and preparation of the specifications and before ordering the plasterboard. On discovering this error, corrections could only be effected by reducing the plaster board after boarding the plaster board to the metal frame. Further, reducing the plaster board created a lot of health and safety issues from dust emissions into the factory. It was time consuming, as it slowed down production speed from the recruited 2 person gang fixing the boards.

What these examples show is the large number of small but significant details that need to be considered in order to achieve productive assembly in the MFF. The overall vision of the approach is to achieve manufacturing levels of productivity but in a temporary factory with low capital costs. These numerous examples of 'on-site' problem solving (although the site here is the MFF) highlight the conceptual issues of how to characterise the early phases of assembly of the cupboards. The process could be considered as an advanced from of site-work in which the repetition and the factory environment allows for quicker refinements of the product and process and the sharing of those refinements. From a manufacturing perspective, the phase of work described in the case study contains many examples that might be seen as inefficiency and waste in the process but might be more usefully to be thought of as a prototyping phase to develop a new product, and solve these myriad small issues before full production.

Selecting the appropriate logic would have implications for the development of the MFF concept and the way it is embedded in the broader construction system. These examples also highlight the interconnectivity of the MFF and its reliance on a design and material supply chain that is unused to designing products for assembly or supplying materials and components to the required level of accuracy. From the perspective of the MFF and optimisation activities, this shows how the supposed discrete activities of the factory cannot be separated from the wider supply chain, and that optimisation is necessary across the supply chain. This is not inconsistent with the principles of lean production, but does re-introduce issues of how to bring about changes outside of the factory environment. This is perhaps a new requirement for the MFF process, and shows how concurrent adaptation is required throughout the supply chain to mobilise the MFF effectively.

2. Lack of storage space

It was found there was a lack of storage space for the materials procured for the production process and for the finished utility cupboards. It was found there is a much greater challenge with the emerging requirement for a 'holding space' for finished utility cupboards that could not yet be taken to the residential project construction site. This was down to variations in the programme on site, and demonstrates the challenges of seamlessly connecting the MFF based production process, with the main construction activity on site.

In order to address this problem, a temporary space was created behind the builder's off-site manufacturing factory for storing the finished utility cupboards, supplied and unused metal frames, and most of the plywood and plaster boards. Storage is not a new issue for the builder but shows the need to develop ability to predict and model storage requirements in a number of scenarios. When faced with a choice of potential spaces, there is a need to balance the risk of over-crowding with the cost of spare capacity - in the case study, the location of the MFF is close to the construction site, in this case, not more than a distance within 20-25 miles radius from the construction site near to the builder off-site manufacturing factory was fortunate.

Whereas the discussion of material specification above showed the interdependence between the MFF and the supply chain, this shows similar connectivity between the factory and the construction site. Although technically the production of the utility cupboards off-site was compatible with the broader project requirements, delays on the project caused the factory to require storage, in lean terms a non-value adding flow.

3. Factory manufacturing space constraints

To reiterate, from the second quarter of 2014, production was anticipated to be at 20 units per week when the factory was at full running capacity. As of now (the beginning of the second quarter of 2015), production is at 15 units per week with a 17 person gang. It may be an unrealistic assumption to believe that the 20 units per week is achievable, because the factory manufacturing space is not large enough to accommodate more trades people and the factory is presently working extra hours including working most Saturdays and Sundays. This shows that there is exploratory work to be done to calculate the relationship between the process, available space in the temporary facility, and potential output levels, regardless of labour resources. This was an unanticipated problem when the 20 units per week were estimated.

Even this relatively simple process is reliant on numerous skilled trades in sequence, and this reveals two issues. The first is that the sequencing of skilled activities around a small component requires space as well as effective coordination. The second is that even a relatively simple process remains dependent on a range of skills, rather than being oriented to semi-skilled labour. This resonates with Höök and Stehn's (2008) assertion that a challenge for lean implementation is the existing pattern and landscape on on-site skills.

4. Lack of skilled personnel and skilled technicians

It was found that there was no skilled technical staff within the company near the MFF site that was conversant with the construction of the utility cupboard. As a consequence, sub-contracting firms were recruited for the boarding, taping and plastering of the cupboard. This was to ensure that there was strict adherence to specification details so that quality requirements were not compromised. However, getting these specially trained workmen when required at the factory was difficult to coordinate. Although this is by no means an unusual problem in site-based work, it does point to the need to consider the division of labour and sequencing of tasks carefully in a small-scale production process. Intermittent use of subcontracted trade operatives was necessary but prevents continuity in the process, and adds potential delays, making it more difficult to develop a factory style continuous process rather than a more site oriented and disjointed set of activities.

The use of skilled trade operatives in the MFF is counter to the, sometimes implicit (Green and May, 2005), goals of de-skilling and multi-skilling for the workforce to reduce costs and increase flexibility. As in the spatial constraints', it also risks perpetuating the project culture and limiting the benefits that can be gained by the application of lean techniques as found by Höök and Stehn (2008). However, our observations also support their conclusion that the creativity and skill of construction trades workers represent a relatively untapped resource for continuous improvement if mobilised correctly.

DISCUSSION AND CONCLUSIONS

This paper defined the MFF with other related topics such as MMC and offsite manufacturing with a clear distinction of the additional benefits and aims of the MFF which is to deliver the benefits of off-site factory assembly, while overcoming the traditional barriers of high capital investment and high transport costs and while also reducing carbon dioxide emission (keeping the environment sustainable) and speeding up the assembly of the building on site by reducing time spent.

Overall, as a pilot the on-going MFF can be seen as a success - the process is now more refined, production is flowing and if anything, it is the variations in progress on-site to enable installations that are the major issues being experienced. But the case is also instructive in terms of developing the concept further, in thinking through the MFF as an area for lean improvement, and in instigating more use of MFFs. There was perhaps an under-estimation of the complexity of the task, and this led to a longer period between setting up and reaching a stage where production was in full swing. Some of the details around potential capability, for instance in terms of numbers of units per week would have been difficult to accurately predict until the assembly process was tested. The final figure of 17 units per week is the MFF operating at full capacity, and this suggests that there is a complex relationship between required output, the 'scope' of the process and the size of the factory. But perhaps above all, the delays for installation on site show that careful consideration of what kinds of activities can be extracted from site, and relocated to a MFF is required. Although technically, certain aspects of site-based activities can be relocated to a factory environment, it is impossible (or at least was in this case) to isolate the MFF from broader interdependencies in the network, whether the supply chain, or the site-based project.

Finally, there is an interesting mix of issues experienced here, some of which are more related to on-site construction and others to factory style production. For instance the subdivision and coordination of labour was an issue - not unusual for construction work and related to the construction of the utility cupboards being reliant on a range of skills, rather than an automated, unskilled or semi-skilled process. Similarly some of the quality issues with components coming into the site could be attributed to the supply chains lack of readiness to provide components with the exact specification and adaptations required for the MFF process. But also issues such as the need for (and lack of) storage space, and the adaptations to the process such as incorporating the stabilizers to enable the cupboard to be moved along the factory as it was assembled are 'classic' production issues. The MFF was set up to sit somewhere between the full scale fixed factory and the building site, and is experiencing some of both in terms of getting up to speed.

Returning to Gann and Salter's (2000) model, the MFF can be positioned as an integrator in a network mediating between material and component suppliers and the construction site (or project). This provides perhaps an unintuitive insight where the factory performs a similar role to any other project based organisation, rather than functioning as a different type of organisation. It is not surprising then, that many of the challenges stem from this mediating and integrating role, rather than the continuous improvement of the factory process itself. A question for further exploration is whether this can be another part of the explanation for the lack of off-site use in construction projects.

The MFF offers a novel way to bring some of the benefits of MMC at much lower economies of scale. There will always be some process improvement required for any new activities but those experienced in this case were straightforward to rectify. There are also some new requirements in terms of supply chain expectations and quality to enable a smoother transition to full operation. But as proof of concept, the case here shows that considerable benefits can be realised with the MFF.

ACKNOWLEDGEMENTS

The authors would like to thank our consortium partners for their involvement in this case, and especially Andrew Skinner and Sam Stacey of Skanska UK for their valuable input into the case study.

The research is part-funded by the Innovate UK's under the 'Rethinking the Building Process' programme: 'Near Site, Off Site - affordable near site assembly in Modern Flying Factories' (Project Reference: 101344).

REFERENCES

Barker, K. (2004*). Review of Housing Supply, Delivering Stability: Securing our Future Housing Needs. Final Report*, March, HM Treasury, London.

Barker 33 Cross Industry Group (2006). *Modern Methods of Construction (MMC) for the Provision of Housing*: *Barker 33 Review - Recommendations*, Barker 33 Cross Industry Group, London.

BIS: Department for Business, Innovation and Skills (2013). *UK construction: An economic analysis of the sector*, July, available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/210060/bis-13-958-uk-construction-an-economic-analysis-of-sector.pdf [Accessed 14 April, 2015]

Boyd, N., Khalfan, M. M., and Maqsood, T. (2012). Off-site construction of apartment buildings. *Journal of Architectural Engineering*, **19**(1), 51-57.

Brydon-Miller, M., Greenwood, D. and Maguire, P. (2003). Why action research? *Action Research*, **1**(1), 9-28

Dubois, A. and Gadde, L. E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction Management and Economics*, **20**(7), 621-631.

Gann, D. M., and Salter, A. J. (2000). Innovation in project-based, service-enhanced firms: the construction of complex products and systems. *Research policy*, **29**(7), 955-972.

Gibbs, A. G. F. (1999). O*ff-site Fabrication: Prefabrication, Pre-assembly and Modularisation, latheronwheel*: Whittles publishing.

Goodier, C. I. and GIBB, A. G. F. (2007). Future opportunities for offsite in the UK. *Construction Management and Economics*, **25** (6), 585-595

Green, S.D. and Harty, C. (2008), Towards a co-production research agenda for construction competitiveness. *Joint 2008 CIB W065/W055 International Symposium*, Dubai, UAE.

Green, S.D., and May, S. C. (2005). Lean construction: arenas of enactment, models of diffusion and the meaning of 'leanness'. *Building Research and Information*, **33**(6), 498-511, Taylor and Francis

Höök, M., and Stehn, L. (2008). Applicability of lean principles and practices in industrialized housing production. *Construction management and Economics*, **26**(10), 1091-1100.

Hooper, A. J. (1998). *Standardisation, innovation and the house building industry.* In Construction Papers, Edited by: Harlow, P. Vol. 95, 3–8. Ascot: The Chartered Institute of Building (CIOB).

Koskela, L. (1992). *Application of the New Production Philosophy to Construction*. Technical Report No. 72, CIFE, Stanford University, CA, 1992.

Koskela, L. (1997). Lean production in construction, in L. Alarcon (Ed.), *Lean Construction*, 1–9. Presented on the 1st workshop on Lean construction, Espoo, 1993

Lawson, M., Ogden, R., and Goodier, C. (2014). *Design in Modular Construction*. CRC Press.

Martínez, S., Jardón, A., Gonzalez Víctores, J., and Balaguer, C. (2013). Flexible field factory for construction industry. *Assembly Automation*, **33**(2), 175-183.

Nahmens, I. and Ikuma, L. H. (2011). Effects of lean construction on sustainability of modular homebuilding. *Journal of Architectural Engineering*, **18**(2), 155-163

Pan, W., Gibb, A. G. and Dainty, A. R. (2007). Perspectives of UK house builders on the use of offsite modern methods of construction. *Construction Management and Economics*, **25**(2), 183-194.

Stokes, C and Dainty, A (2011) Knowledge co-production in construction management research. In: Egbu, C and Lou, E C W (Eds.), *Proceedings 27th Annual ARCOM Conference,* 5-7 September 2011, Bristol, UK. Association of Researchers in Construction Management, 117–26.

UKCES: UK Commission for Employment and Skills: (2013), *Technology and Skills in the Construction Industry*. Evidence Report 74, September, London,

Vrijhoef, R., and Koskela, L. J. (2005). Revisiting the three peculiarities of production in construction. In *Proceedings of 13th International Group for Lean Construction Conference*. (pp. 19-27).