DESIGN OF A LEAN AND AGILE CONSTRUCTION SYSTEM FOR A LARGE AND COMPLEX MECHANICAL AND ELECTRICAL PROJECT

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ABSTRACT

This paper represents "work-in-progress" as part of a collaborative research project being undertaken at the Centre for Innovative Collaborative Engineering for an Engineering Doctorate at Loughborough University, UK. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the sponsor company). The project will have specific objectives, which will be capable of making a significant contribution to the performance of the company.

The sponsor company is developing a "construction system" in order to improve the performance of its projects, and earlier research in this field has shown that lean interventions, when applied to a case study project, has had positive results. This paper describes the next phase of the development of the construction system, and proposes a lean and agile production system model which is to be implemented on a major private finance initiative (PFI) hospital development, and in particular the mechanical and electrical (M&E) elements.

The model builds upon a "leagile" concept developed from manufacturing theory, and shows how the need for leanness and agility depends upon a total supply chain and labour strategy.

KEY WORDS

Construction system, performance improvement, lean interventions, lean and agile, mechanical and electrical, leagile, total supply chain, labour.

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INTRODUCTION

This paper represents "work-in-progress" as part of a collaborative research project being undertaken at the Centre for Innovative Construction Engineering for an Engineering Doctorate at Loughborough University, UK. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the company). The project will have specific objectives, which will be capable of making a significant contribution to the performance of the company.

The themes of the research project are "Innovative Construction Technologies" driven by the desire to use leading edge research and learning to improve the business of the sponsoring company. The sponsor company is a major provider of advanced mechanical, electrical and communications solutions in the construction sector in the UK. It works for customers in banking, retail, leisure and commercial property development, as well as education, health, defence and government offices, secure establishments and airports.

RESEARCH PROJECT OBJECTIVE

To be clear about the objective of this project for the company, it is about improving site operations, making them safer for the worker, and improving efficiency and productivity. The initial objective was about improving the performance of its projects in terms of productivity, and previous research was conducted by Court et al. (2005), implementing lean interventions on a case study project, which had positive results. Since then, an incident and injury free programme has been introduced, and the safety leadership team state that the company is prepared to invest whatever is necessary to drive improvement in health and safety to ensure everybody returns home safely. "Failure to do so renders the company valueless", it is said. Also, the company is embarking on a programme of improving the performance of its projects by the introduction of a "project delivery standard". One component of this standard is to "adopt lean and agile processes to compete with the worlds leading businesses". From this, the key elements to focus upon as further research project objectives are therefore:

1. To be incident and injury free (everyone is to return home safely)
2. To adopt lean and agile processes to compete[5] with the worlds leading businesses

This project therefore has the objective of designing and implementing a way of working on site that will satisfy these company objectives; to be incident and injury free and to adopt lean and agile processes to compete with the worlds leading businesses. As mentioned previously, earlier research by the authors implementing lean interventions were to form part of the design, together with new lean features, of a "construction system", which is based on leading edge research and learning.

This paper describes the next phase of the development of the system, and proposes a lean and agile construction system which is to be implemented on a major private finance initiative (PFI) hospital development, and in particular the mechanical and electrical element and the associated interfacing trades. The system design builds upon a "leagile"

[5] To compete: To strive consciously or unconsciously for an objective (as position, profit, or a prize): be in a state of rivalry (Merriam-Webster online dictionary)

concept developed from manufacturing theory, and shows how the need for leanness and agility depends upon a total supply chain and labour strategy. In order to gain an understanding of the development of the system, the underpinning manufacturing theory will be described, together with further data collected necessary to aid the design and development of the construction system. The construction system itself will then be described. Finally, the expected benefits to the company as a result of this research project will also be described, along with further research still to be undertaken.

UNDERPINNING THEORY

Manufacturing is seen as a rich source of research data for lean and agile concepts, therefore this was a primary source of theory for this project. The next phase of the project has focussed upon this research and the learning obtained has helped to provide an interpretation of what adopting lean and agile processes actually means, and how to put this into practice in the real world, via this project. The research and learning has been used to develop a construction system that incorporates manufacturing techniques such as; leagility, modular assembly, reflective manufacture (including pulse driven scheduling), and ABC inventory analysis. Each of these concepts is now reviewed.

LEAN AND AGILE MANUFACTURING - LEAGILITY

According to Mason-Jones et al. (2000) lean and agile paradigms, though distinctly different, can be and have been combined within successfully designed and operated supply chains. They defined leagility, which follows from the paper by Naylor et al. (1997), as:
"…the combination of the lean and agile paradigm within a total supply chain strategy by positioning the decoupling point so as best to suit the need for responding to a volatile demand downstream yet providing level scheduling upstream from the decoupling point".

Techniques in lean tend to suit the highly efficient producer, particularly the production of high variety commodity items at minimum cost. Lean is efficient but can it also be responsive? Lean seems to be much more appropriate for efficiency and cost cutting. Agility stresses different values to lean, typically learning, rapid configuration, and change. However, lean and agile may be complimentary in the sense that you can join one system to another. For example a lean factory could be joined to an agile supply chain. The coupling of "Lean" and "Agile" is often known as "Leagile". Following this logic a factory can be linked to its supply chain in three possible ways, and this is shown in table 1. Agility is the ability to rapidly reconfigure the production system (and the supply and distribution systems) to meet new product requirements. Agility has a responsiveness dimension which does not seem to be part of the lean definition.

It is possible to link different sorts of systems together using the concept of the decoupling point. For example the lean factory can be separated from the agile distribution chain by means of a decoupling store. The factory will produce modules that are placed in the store and as the demand changes the modules can be quickly assembled in the distribution chain to provide the customer with a unique offering. Simchi-Levi et al. (2003), describe various ways in which product design interacts with supply chain management to increase responsiveness to market changes.

Table 1: Three ways to link a factory to its supply chain

Factory	Supply Chain	Product Type
Efficient (lean)	Efficient (lean)	Commodity items with predictable demands
Efficient (lean)	Responsive (agile)	Mass-customised items
Responsive (agile)	Responsive (agile)	Fashion or innovative products with unpredictable demand

If the decoupler is moved very close to the customer so that it is far downstream then you have a "form postponement" strategy where the module store is close to the retailer and they have the means to rapidly assemble the product to meet the precise customer order. If the distribution of the product is delayed to the last minute and only configured and distributed when the customer order is received then you have "logistics postponement". Ulrich and Eppinger (2004) explain examples of how product architecture enables postponement, which is the delayed differentiation of the product, until the exact customer requirements are known.

Postponement therefore implies major changes to the systems of production and distribution. The factory produces a range of modules that enable high variety products, and can be quickly assembled into final form. With form postponement the retailers are provided with simple fixtures with all tools that enable them to rapidly configure the product to meet the customer's requirement. Such a strategy provides mass customisation. A form postponement decoupler is shown in figure 1.

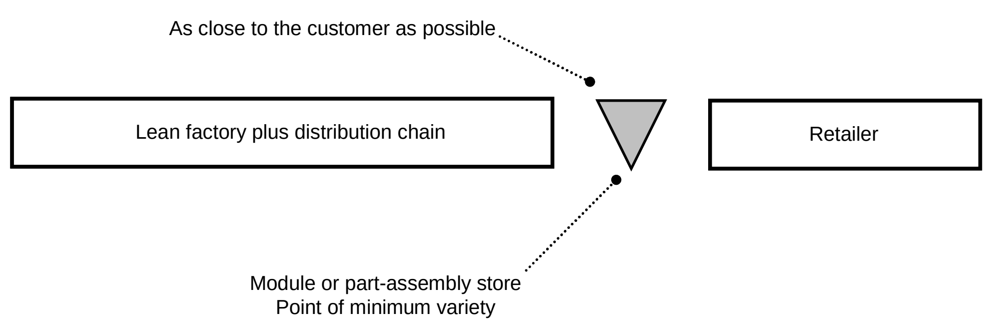

Figure 1: Product Stream

The leagile concept, combining lean and agile paradigms, are at the core of the construction system, which shall be shown later in this report.

MODULAR ASSEMBLY

According to Fredriksson (2006), modularity[6] is a design strategy that is used by companies producing such different products as aircraft, household appliances, trucks and cars, computers and software. The popularity of the concept he describes, is explained by its appealing logic, which is to divide a complex system into decoupled and manageable modules that are easily put together into a working whole. A definition of this is given as:

"…the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks".

Modularity in production thus implies a dispersed assembly system, in which some activities are pre-assembly (of components into modules) and other activities are final assembly (of components and modules into end-products). This is shown in figure 2.

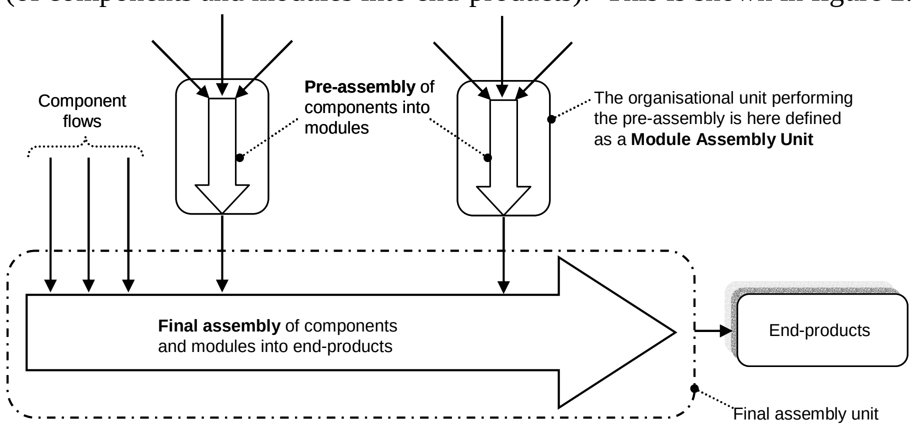

Figure 2: Modularity in production (Figure 1 in Fredriksson 2006)

Modular assembly is an important component of the construction system and its function shall be described later in this report.

REFLECTIVE MANUFACTURE AND QUALITY OF WORK

Reflective manufacture is an important socio-technical approach to manufacture that arose in Sweden at the Volvo Uddevalla plant. Its evolution is described by Granath, (1998). It was regarded in Sweden as a person centred approach to automobile assembly although it was never fully developed. It is now attracting more attention with the development of mass customisation strategies. Reflective systems do vary in the way that they are designed; however, they tend to suit a highly modularised product. Also, research has found that Volvo, when looking into the development of production systems, looked into quality of work as well as efficiency of production. Quality of work,

[6] Modularity: Also referred to in this report as modular assembly, offsite manufacture, standardisation and pre-assembly, all of which are derived from referenced research reports. IGLC championship defines this as prefabrication and assembly

according to Granath, contains a number of aspects. He suggests that a system that offers professional meaningful work is better than those that only offer unskilled or semi-skilled work. The aspects that signify professional work are control over methods, time and quality plus the responsibility to plan ahead and the knowledge needed to reflect on work done. Quality of work also means good ergonomics, appropriate working tools and a good working environment. A typical form of reflective system generally has module build units or cells each the responsibility of a semi-autonomous team. Team members are multi-skilled and highly trained so that they are interchangeable. There are likely to be standard operating procedures (SOP's) but members themselves generally design these. In these systems there is often a significant materials acquisition unit with a kitting function. The system operates using the "pulse" system or period batch control. Period batch control (also know as period flow control) is a just-in-time, flow control, single cycle, production control method, based on a series of short standard periods generally of one week or less (Burbidge, 1996). Alternatively, the system operates using an ABC inventory system (described later). Figure 3 shows a typical system.

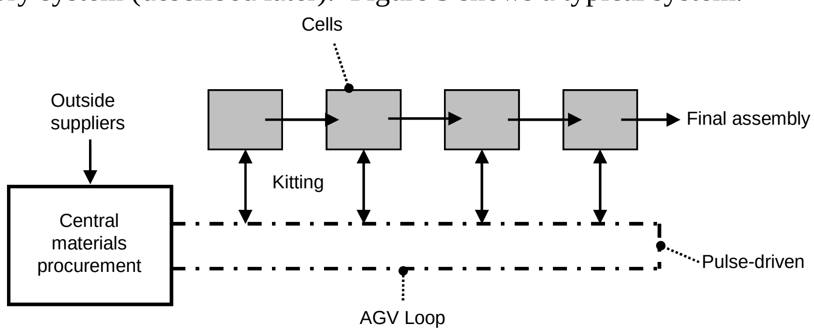

Figure 3: Reflective System

This approach suits a postponement strategy as shown in figure 4. Here modules are combined with parts once the exact customer requirements are known.

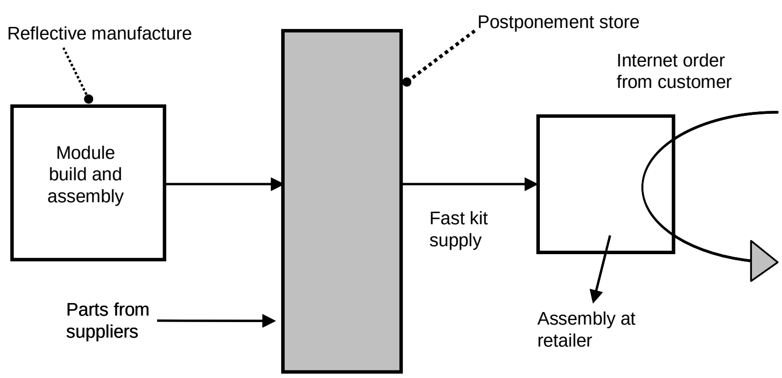

Figure 4: Postponement Approach

The concepts described here, reflective manufacture (including quality of work) and the postponement approach shown in figure 4, have significantly shaped the design of the construction system and this shall be shown later in this report.

ABC INVENTORY ANALYSIS

An important feature of reflective manufacture is the ABC inventory system, referred to earlier. ABC inventory analysis is based on Pareto analysis or the 80/20 rule. In inventory control 80% of the items need 20% of the attention, while the remaining 20% need 80% of the attention. They are categorised as follows: A items are expensive, critical and needing special care. B items need just standard care, and C items need little care. It is common to use different control strategies for the A, B and C parts. The control strategy depends upon the product complexity and the nature of demand, but typically: A parts are ordered using a "call-off" system, B parts are ordered conventionally using an MRP system, and C parts are ordered using a simple inventory management system like the two bin kanban system.

It will be shown how the supply chain within the construction system has been categorised using this method.

These collective manufacturing concepts previously described have been used to shape the design of the construction system, together with further data collected, which is now described.

FURTHER DATA COLLECTION

During the course of the design of the construction system, further data was collected for the design of trade team specific mobile work cells and methods of material delivery to the workplace. This was conducted in a focus group session with representatives from electrical workers, mechanical pipe workers, and duct workers.

The aim of the focus group session was to identify the complete kit required for each specific task to be completed at each stage of the site operation, with everything that is needed, factoring in: access and egress to and from the work place, access equipment, tools, personal protective equipment, materials handling devices, and task lighting etc. It also included discussions on how material flows should be conducted on site, to the point of use. This data was collated and used to design trade team specific mobile work cells, and the work system itself. This builds upon the previous research by Court et al. (2005), implementing mobile work cells and ergonomic access equipment designed and used in a case study project.

In order to formulate an understanding of manufacturing concepts in the context of this research, an ethnographic study was also undertaken. This was an observational study conducted at the BMW "Mini" factory in Cowley, UK. This was to observe the assembly of the car body and the final car assembly process, to give the authors a "feel" for the manufacturing and assembly environment, and how people worked. It is not meant here to expand upon the Mini manufacturing process, but more importantly, the authors, by observing the various assembly processes conducted either by robots or people were able to get many visual clues as to how the techniques could be transferred to the construction system model.

THE CONSTRUCTION SYSTEM

The construction system is the proposed methodology to deliver the objectives of the sponsor company. It builds on previous research by the authors, Court et al. (2005), which found that lean interventions, when applied to a case study project, had positive results in terms of improving the performance of the project. These interventions were the first stage of designing and implementing a construction system for the company. The findings from this research were to be used to inform and develop standardised operating procedures and routines for how work will be conducted in the future on new projects. This was to be together with new lean features to be researched, developed, implemented and tested on these new projects, which would be reported on in the future. The development of the construction system represents this next phase of research, and has been designed for, and is to be implemented on a case study project.

The construction system model is represented in figure 5. Its underpinning theory has been described earlier in this report, and incorporates manufacturing concepts such as leagility, modular assembly, reflective manufacture, and ABC inventory analysis.

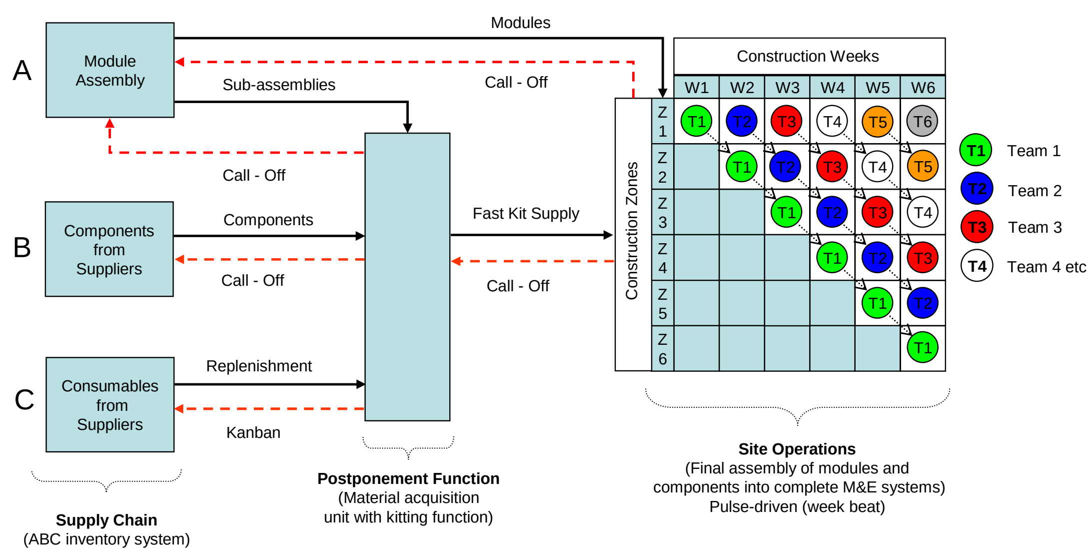

Figure 5: Model of the construction system

Its key components are its supply chain, the postponement function and its site operations. These are now described.

SUPPLY CHAIN

The supply chain has been categorised using ABC inventory analysis, with modules (category A) being delivered directly to site on a call-off system. Components and consumables (category's B and C) shall be parts kitted for delivery to site via the postponement function also on a call-off system and to the exact requirements for the site operations. Table 2 shows examples of the materials ABC categorisation.

Modular Assembly

A key component of the supply chain are type A materials, which are pre-assembled modules. For the case study project, the M&E systems have been designed for modular assembly (off site manufacture), and will be complete assemblies or sub-assemblies as appropriate. Examples of these are shown in figure 6; a corridor services module, and figure 7, a distribution module.

Table 2: Examples of Materials ABC Categorisation

Type A Materials	Type B Materials	Type C Materials
Plant room modules, distribution modules, riser modules, corridor modules, bathroom pods, IPS units, modular operating theatres, modular walls etc.	Cables and electrical accessories, loose pipes and fittings, ventilation components (ductwork, grilles, dampers etc), radiators, heating panels etc.	Nuts, bolts, screws, washers, mastic, fixings, consumables for power tools etc.

Table 2 shows examples of the elements of the M&E systems which are to modularised (type A materials). The modules shall be delivered directly to site, in the exact sequence required, and shall be incorporated into the final systems through a small and simple series of tasks by the trade teams.

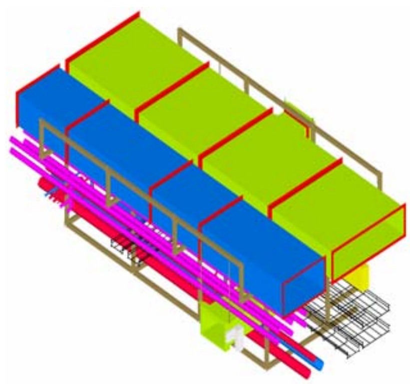

Figure 6: Corridor Module

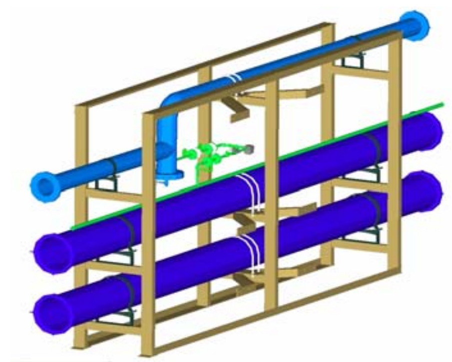

Figure 7: Distribution module

The materials that are not provided on the modules, which form the systems that radiate from them, are to be delivered in kit form via the postponement function.

Postponement Function and Parts Kitting

As has been described, the system operates using an ABC inventory system, where materials have been categorised accordingly and will flow directly to site, or via the postponement function for kitting prior to being sent to site on a just-in-time basis. Postponement here refers to the kits of materials (type B and C) being postponed until the moment they are needed, which are "called-off" by the trade teams to suit their specific requirements, this being a derivative of "form" postponement described earlier.

A related form of the postponement concept has previously been implemented at the T5 programme, Heathrow Airport, called the market place for demand fulfilment, and this is for civil works consumables, personal protective equipment, hand tools, power tools and consumables for power tools. This was the subject of the paper, “Kanban in Construction”, Arbulu et al. (2003).

It is expected that this research will help shape the further detailed design of the postponement function and parts kitting method for the construction system. The postponement function and the materials ABC inventory analysis will be the subject of further research leading its design and implementation on the case study project.

SITE OPERATIONS

Site operations shall be conducted by semi-autonomous trade teams (T1, T2 etc), using mobile work cells and ergonomic access equipment as described by Court et al. (2005), and specifically designed for their individual activity. The system operates using a “pulse-driven” system, which has been called the “week beat”. Production control will be facilitated using the last planner production control system.

Trade-Teams, Mobile Work Cells and Ergonomic Access Equipment

Semi-autonomous trade teams shall be deployed on site with mobile work cells and ergonomic access equipment. The work cells shall be designed specifically for the trade teams, using data collected from the focus group research exercise discussed earlier, and builds upon the previous research in this area by Court et al. (2005).

The specific purpose of these interventions is to eliminate unnecessary motions for the tradesman getting to the place of work, and to have the necessary tools, components and consumables at hand to carry out the work uninterrupted. This is intended to facilitate an environment for “quality of work” as described by Granath (1998).

Pulse-Driven Scheduling

The system operates using a “pulse” system, which has been called the “week beat”. Here, each team has one week in each construction zone (approximately 1000 square meters) to complete its work before moving to the next zone. The next team, T2, follows on at the week beat interval, and the next, T3, team follows similarly. Requirements for the week beat are that each team has to work at the rate at which the previous team makes the working area available to them, so as to provide a continuous flow of work. The size of each team may be increased or decreased but the actual pace of physical effort is never changed. Each team has to carry out their designated amount of work in the planned time so as to make the working area available for the subsequent trade. Timing has to be such that each team can complete their work in the zone and move to the next zone without waiting for it to become available or starting early. The rate at which each item of work is carried out is to pull kits of materials onto the site, to the point of use, on a just in time basis, specifically for the task, on mobile carriers or roll cages. Access equipment and tools shall be designed specifically for the area in which the work is to be carried out, and for the rate at which the work is to progress. The rate at which each item of work is carried out is to pull drawings and information onto the site, being always the latest, most up to date and approved for construction.

A similar method has been implemented on previous case study projects; see Court et al. (2005) and Horman et al. (2002).

Other System Features

Other lean features of the construction system which will be deployed are the last planner system of production control, and IMMPREST[7]. Last planner is a production planning and control tool used to improve work flow reliability. According to Henrich et al. (2005), it adds a production control component to the traditional project management system. This method is being employed through the various stages of the case study project, starting with the design phase. IMMPREST is an interactive tool to measure the risks and benefits of using prefabrication within a construction project, see Pasquire et al. (2005).

DISCUSSION

The construction system described builds upon a "leagile" concept developed from manufacturing theory that incorporates techniques such as; leagility, modular assembly, reflective manufacture, and ABC inventory analysis. It shows how the need for leanness and agility depends upon a total supply chain and labour strategy. The supply chain strategy is clear; to pre-assemble as much as possible off-site (category A materials), to be delivered just-in-time, and incorporated into the final assembled systems along with component kits (category B and C materials) in a series of small and simple tasks. The labour strategy is also equally as clear; to remove as much labour off site as possible, and those that remain shall be provided with good ergonomics, appropriate working tools and a good working environment, thereby facilitating a "quality of work".

Previous research by Childerhouse et al. (2002), and Naim et al. (1999), proposed a leagile model to be applied in construction, and in particular house building in the UK. The agile dimension providing flexibility of customer choice at various stages in the house building value chain, and is a robust and valid model. The customer here is the end user, or the purchaser of the house. The system proposed in this paper provides an alternative proposition to leagility in construction. The customer requiring flexibility in the construction system is the construction site itself, and in particular the semi-autonomous trade teams requiring exactly what they need and when they need it; this is the agile dimension. The lean dimension being the site operation component designed to eliminate the waste usually experienced if interventions are not made to eliminate them. Also, the postponement function will act as a buffer to the site to account for variability that may occur.

Much research covering modularity[8] in construction has been conducted, Pasquire and Connolly (2002), Pasquire and Connolly (2003) and Construction Industry Research Association, (1999), which has dealt with this concept, and according to Ballard and Matthews (2004), a lean ideal for the championship, prefabrication and assembly, is to "simplify site installation to final assembly and commissioning". The authors believe that the contribution to this research is how modularisation can be incorporated into a wider construction system, in the same way that manufacturing has used this strategy, as is used in reflective manufacture. It is also expected that by implementing a strategy of modularity, health and safety risks on site will be reduced. HASPREST[9] is a tool which

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[7] Interactive Model for Measuring Preassembly and Standardisation in construction

[8] Modularity: Also referred to in this report as modular assembly, offsite manufacture, standardisation and pre-assembly, all of which are derived from referenced research reports. IGLC championship defines this as prefabrication and assembly

[9] The effect of Standardisation and Pre-assembly on Health, Safety and Accident Causality in Construction

will be used to establish the extent of the effect of standardisation and pre-assembly on health, safety and accident causality in construction. Benefits will be obtained by being able to include health and safety aspects in the consideration of modularity. A further benefit to applying modularity in construction is reducing the risk to projects due to skills shortages in the UK. Goodier and Gibb (2005), in a research project looking into barriers and opportunities for offsite (manufacture) in the UK found that electricians, joiners and bricklayers were the three skills generally cited the most by all the sectors questioned as being in short supply and contributing to the increased demand for offsite products. Off-site manufacturing reduces the quantity of on-site labour thereby reducing the risk of skilled labour shortage. The expected benefits of the system to the company are that health and safety shall be improved facilitated by reducing the number of workers on site, and those that remain are provided with good ergonomics. Also, productivity shall be improved by implementing the lean interventions on site, thereby eliminating the normal waste that occurs had these interventions not been made. Finally the company may have found a way to adopt lean and agile processes, and because of this, in the opinion of the authors, will be positioned to compete with the worlds leading businesses, as the new standard requires them to do so.

Although it is not the subject of this paper, an interesting matter for discussion is the influence the construction system will have on project management. Whilst the construction system has been received well by the company, in particular the projects sponsors, it is very much seen as research and development, and “let’s see how it goes”. It has also been well received by the immediate project team as it has been developed alongside them, stage by stage. Also, the authors have considerable influence on the case study project (one of the authors is the M&E project leader), and in this respect there is no alternative to its implementation. The system is very much an intervention into what would otherwise be normal project management practices. Its influence on project management may well be worthy of a research study on its own.

FURTHER RESEARCH

The next phase of research will be conducted by applying the construction system to a case study project. The project selected is the mechanical and electrical (M&E) element of a large Private Finance Initiative (PFI) hospital, to be built in phases over a five year period, and an M&E value in excess of £100 million. Further research will also be undertaken to design in more detail certain elements of the construction system. These are: developing the ABC inventory system by standardising modules, components and consumables into a project catalogue; the postponement function with the fast kit supply methodology; developing the week beat system and further designing “quality of work” for the worker. The results emerging from this and the construction systems implementation on the case study’s initial phases will be reported on in future papers. Finally, the authors intend to understand the construction system in the context of the emerging theory of “construction physics”, and this may feature in the next phases of research for this project.

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