TRANSFORMING TRADITIONAL CONSTRUCTION INTO A MODERN PROCESS OF ASSEMBLY USING CONSTRUCTION PHYSICS

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ABSTRACT

This paper presents the outcome of an engineering study as part of the design and development of a lean and agile construction system and in particular its lean site operations component, to be subsequently tested on a case study project (not reported here). The objective of the system is to improve health, safety and productivity for the company sponsoring the research.

The research uses Construction Physics theory as the main framework to design the flows feeding the construction system to ensure the process is sound. Also, with the use of pulse-driven close-scheduling techniques the research shows those overall task cycle-times can be significantly reduced, further contributing to productivity improvement for the company. By managing the seven precondition flows forecasted onsite labour is reduced by 35%, together with a 20% reduction in construction zone cycle-time. This reduced onsite labour means less workers are exposed to health and safety risks and by using modular assembly with ergonomic workplace design an improved quality of work is provided for those workers that are required on site, carrying out simpler assembly tasks as a result of the construction system. Productivity gains will be realised by the system acting as an antidote to the waste that traditionally occurs in M&E construction, therefore enabling the planned work to be carried out within the labour cost centre budgets.

KEY WORDS

Construction system, Construction Physics, lean site operations, health, safety, productivity.

INTRODUCTION

This is a practical paper drawn from a collaborative research project (the research project) being undertaken at the Centre for Innovative Collaborative Engineering at Loughborough University, UK. The programme is funded by the Engineering and Physical Sciences Research Council (EPSRC) and is sponsored by a major UK mechanical and electrical contractor (the company). The research project has specific objectives, which will be capable of making a significant contribution to the performance of the sponsor company. The company is developing a construction system in order to improve the performance of its projects and earlier research in this field (Court et al.

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2005) has shown that lean interventions when applied to a case study project had positive results. The next phase of the research (Court et al. 2006) using leading edge research and learning, designed 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 (M&E) within it (the case study project). The system has two primary components, which are its supply chain with a postponement function and its lean site operations. This paper describes the next phase of the research project, which is the design of the lean site operations, combining pulse-driven close scheduling and ergonomic workplace design. The paper uses Construction Physics theory as a conceptual framework in which to describe the soundness of the process as designed. The supply chain component is the subject of further research prior to its implementation on the case study project.

PROJECT OBJECTIVES

The objective of this project for the company is to improve site operations, making them safer for the worker and to improve productivity. Safety is at the core of the company and according to the business leaders, *"…it is an absolute right for people to return home safely at the end of a productive day's work"* and *"…failure to do so renders the company valueless"*. Considering these statements, the key words are *"safely"* and *"productive"* so these are therefore the key themes and objectives of this research project, which is to design and implement a way of working on site that will satisfy these objectives.

UNDERPINNING RESEARCH

Manufacturing is seen as a rich source of research data for the adoption of lean and agile concepts into construction, therefore this was a primary source of theory for this research project. The research and learning has been used to develop a construction system that incorporates manufacturing concepts such as; modular assembly, postponement, reflective manufacture and ABC parts classification. These were reviewed and described in Court et al. (2006).

FURTHER RESEARCH: CONSTRUCTION PHYSICS THEORY

Construction Physics is a theory based understanding of the nature of the flows and their interactions in the construction process. In the paper by Bertelsen et al (2006), a proposal is made to the IGLC community to put together a large number of contributions on construction flow to create a flow model of the construction process and thereby reach a deeper understanding of its nature – a Construction Physics. It considers construction as a continuous process being fed by a number of streams, where the content of these streams decides the actual outcome.

Construction Physics deals with the flow of all the prerequisites which make the process sound and it considers as an outset these flows as equally important for the soundness of the process. It is explained in the paper that by a sound process it is understood that all prerequisites are in place and where an operation can be performed without delay. Also looked at is the interaction between the flows such as how the flow of materials influences the flow of space. An example of this is where materials stored on site unnecessarily causes obstruction to following trades, thereby preventing them from performing their operation without delay (Winch and North 2006). In looking at the interaction between flows, Construction Physics aims to identify and act in the flow, or combination of flows, which contain slow rates of productivity, discontinuity, constraints, and bottlenecks for the whole system. Bottlenecks in work systems are the subject of the theory of constraints (Goldratt and Cox 2004). These latter points are important to the construction system, because during its design, constraints and bottlenecks were identified and if countermeasures were not made to overcome them, would have an adverse affect to the operation of the system. These are discussed later in this paper.

Bertelsen et al. (2006) discuss the origins and meaning of the flows feeding the construction process and present seven precondition flows, these are; previous work; space; crews; materials; equipment; information and external conditions. The relevance of Construction Physics and these seven precondition flows to this research project is explained later in this paper, but the authors believe that this is an appropriate conceptual framework in which to describe and then test the components of the construction system. In Court et al. (2006) it was said that the authors intend to understand the construction system in the context of the emerging theory of Construction Physics and it will be seen later that the description of the lean site operations component of the construction system considers this.

THE CONSTRUCTION SYSTEM

The construction system is the proposed methodology to deliver the objectives of the sponsor company which builds on previous research by the authors, Court et al. (2005) and is represented in figure 1. Its underpinning theory incorporates manufacturing concepts such as modular assembly, postponement, reflective manufacture, and ABC parts classification and was described in Court et al. (2006).

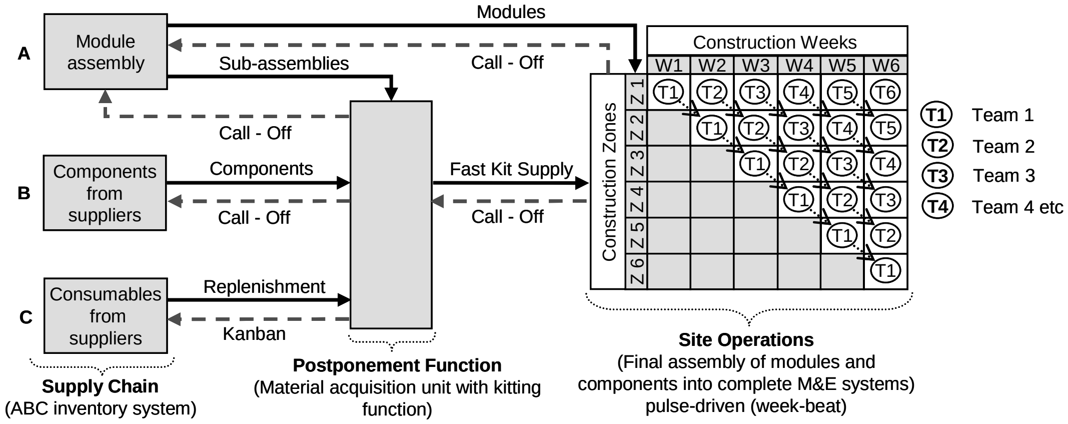

Figure 1: The construction system (Figure 5 in Court et al. 2006).

Its key components are its supply chain with a postponement function and its lean site operations. The supply chain component has been categorised using ABC parts classification, with modules (type A) being delivered directly to site on a call-off system. Components and consumables (type B and C) being 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, with the kit delivery being postponed until the moment they are needed. Site operations are conducted by semi-autonomous trade teams (T1, T2 etc), using mobile work cells and ergonomic access equipment as described by Court et al. (2005), being 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. The supply chain component is the subject of separate research studies prior to its implementation on the case study project. This paper describes the design of the lean site operations component of the system and its application to the case study project.

THE CASE STUDY PROJECT

The case study project is part of the development of a major acute hospital being procured using the UK Government's Private Finance Initiative (PFI). The project is to be developed in phases across two existing operational hospitals. The construction system is being applied on each phase of the case study project the first being the new Maternity and Oncology Centre. This is a 20,000 m² building over four floors which has electrical and water storage plant rooms in its basement with main ventilation plant rooms over the Oncology Centre at level two and on the roof at level five. Riser shafts are located around the building and distribute air, water, medical gas, electricity and the like throughout the building to the various departments. Corridor ceiling voids distribute the services from the riser shafts and then further into individual rooms and spaces, again in the ceiling voids. Finally, services distribute inside dry-lined walls to points of use such as electrical sockets, sinks, basins and bed-head units; everything you would expect to see in a new and modern healthcare facility. As discussed earlier, the authors intended to understand the construction system in the context of the theory of Construction Physics, so its operation is now described within this conceptual framework.

CONSTRUCTION PHYSICS: USING THE SEVEN FLOWS

The seven precondition flows of Construction Physics have been discussed earlier and are; previous work; space; crews; materials; equipment; information and external conditions. The order of these as reported in Bertelsen et al. (2006) has been changed to allow a better descriptive flow in the context of the lean site operations of the construction system.

FLOW OF INFORMATION

The primary method on the case study project to create construction information is the use of digital prototyping (3D drawing). This process enables digital visualisation and co-ordination, as well as the ability to schedule parts from the model. A project digital library is populated with objects that the company already possess, together with those provided by suppliers and component manufacturers. It has been made a pre-requisite that suppliers provide digital objects for their components in the purchase agreements, to avoid the need for the company's modellers to develop these from scratch. Also, ductwork manufacturing drawings are produced from the model, allowing direct transmission of data to the company's preferred suppliers CAM (computer aided manufacturing) software and machinery. This avoids the waste of reproducing manufacturing drawings from normal 2D layouts. Modular assemblies are also objects within the model, which in turn have individual manufacturing drawings associated with them. The model generates single service drawings, each being a layer from the parent model which is coordinated and free of clashes. Actual drawings required in the process are printed from the model into paper-space for use in the manufacturing and construction processes as required. A collaborative web-based document and information management system is deployed on the project which manages the flow of information from the project to the supply chain and those requiring information.

FLOW OF MATERIALS

The M&E systems and components for ABC parts classification were agreed upon according to principles, parameters and ground rules pre-agreed by a cross-functional team. Liker (2004) called this set based concurrent engineering. This term was used to describe how Toyota developed vehicle designs using a cross-functional team of experts and the project leaders relied on that team. This was the starting point for deciding upon what chunks of the M&E systems were to be modularised (type A parts) and what would be parts kitted or replenished (type B and C parts), as well as the selection of the actual components themselves. Because ABC parts are procured according to their type, their supply chain source needed to be understood. To assist this parts were further categorised into made-to stock and made-to-order type. 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. In this lean ideal products used in the building process have been divided into made-to-stock (MTS) and made-to order (MTO).

When designing this system, of concern to the teams was the potential fragility of the system. A production system which culminates with just-in-time (JIT) is very efficient if everything runs perfectly, but is extremely fragile if there is any kind of problem whatsoever (Forza 1996). Further, in order to be able to function in a lean system, all the resources being used in the production process have to be foreseeable and reliable. The construction system has the potential to be fragile in this way as it is not embedded in company operations and tried and tested. Therefore component flows into the project have to be foreseeable and reliable in order for the construction system to work as planned. Safety stock and safety lead times[5] can be used as protection against these problems (Hopp and Spearman 2001). Safety stock is used to protect against uncertainties in production and demand quantities, while safety lead time is used to protect against uncertainties in production and demand timing. These have been built into the construction system with resource capacity buffers built into site operations, as discussed later in this paper. Safety stock in the system has been provided both on site and in the supply chain for MTS type B and C parts. These parts are purchased from national framework suppliers and held in stock at a local branch. The kits provided to site are delivered today for use tomorrow giving a one day stock buffer on site. A construction zone[6] takes one week to complete in the week-beat cycle and supplier's agreements are to keep two zones of parts in stock at the local branch. Replenishment is signalled when parts for a zone have been depleted, giving a week safety stock buffer in the system, but

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[5] The word safety used here refers to security of parts supply in a production system which is to be differentiated from the same word used in health and safety but meaning the well-being of the worker.

[6] The case study project is divided into construction zones, each being approximately 1,000m². This is described later in this paper.

offsite. Site replenishment from the local branch signals replenishment from the central warehouse to the local branch, who replenishes it with a zone every week. The central warehouse operates a 12 week stock-turn giving an 11 week safety stock buffer further back in the system. This relies on global project quantities being advised by the project to the supply chain, which has been done. Safety lead time in the system is provided in the supply chain for MTO type A and B parts. MTO type A modules given their size and complexity are required to be delivered directly to the point of use and their lead time has been incorporated into the master schedule. A safety buffer of at least two weeks has been built-in dependant upon the module type to protect against any disruption to production and site demand. MTO type B components have a lower lead time than modules and again safety lead time for these has been built into the master schedule to protect against any unforeseen problems that may occur.

Construction Zone Modules (type A parts)

Corridor modules are assembled in the companies manufacturing centre and are transported to site in batches of four on assembly, transportation and installation frames (ATIF's). These are lifted with mechanical hoists and bolted to cast-in unistrut inserts running in tram-lines along corridor positions in the concrete soffit. Each construction zone has approximately 15 modules and four are fitted per day, completing each zone within the week-beat period. Riser modules are also assembled at the manufacturing centre and these are single storey risers containing pipework, ductwork or electrical components, or any combination of the three. A steel riser floor is cast-in to the concrete slab as these progress, with each pipe, duct or bus-bar opening pre-cut and capped off, which is removed just prior to the riser being positioned. The height of the riser is less than the slab to soffit height, allowing it to be wheeled into position. With stool pieces previously fitted through the pre-cut riser openings to connect to the riser below, the ATIF frame deploys the riser onto these stool pieces, which is then connected together. The ATIF is then returned to the manufacturing centre for re-use.

Construction Zone Component Flows (type B and C parts)

The approach to manage the flow of components to the point of use has been described earlier in this paper, which is to kit the specific parts for the MEP operation and postpone its delivery until it is needed. The kitting itself is carried out using MTO and MTS suppliers as re-packing centres and de-coupling points. Bertelsen et al. (2006) describe previous experiments using this approach. Each of the components is selected to be quick-fit, commercially available and tried and tested technology. Small pipework for water and drainage is either push-fit, crimp-fit or clamp type. Larger pipes are welded and flanged, but made offsite. Electrical trays are basket, trunking or ladder type which fit together quickly with snap-on couplings. Power cables for small power and lighting is a modular plug-and-play connectable system configured on site from standard MTO components. Larger armoured cables for main power supplies are standard type MTO and delivered on large cable drums. Low voltage cables (data, BMS, nurse call etc.) are also standard items on small drums or boxed as appropriate. Each of these components are delivered to site in purpose made roll cages or similar. Where components can be assembled together operatives and tools are provided at the local supplier's branch to pre-form conduits and assemble pipe clips onto brackets and the like. Plant rooms are divided into manageable chunks, which are: plant items, plant room modules and distribution modules, all of which are MTO. Plant components such as pump sets, pressurisation units, valve stations etc. are grouped together and assembled into plant room modules offsite by the company. These are wired and insulated at the manufacturing centre to further reduce the amount of work on site.

FLOW OF PREVIOUS WORK

To manage the flow of previous (connecting) work a detailed analysis of the installation sequencing was undertaken using cross-functional teams, with particular emphasis on ensuring that no two or more trades would work in the same place at the same time unless allowed to do so. This will prevent crews interfering with each others progress and provide an uninterrupted flow of work. The building is divided into construction zones each being approximately 1,000 m² (zones 1-17, plantrooms 1-3). This area of construction zone being right-sized for each trade team[7] to complete the planned work within five days. Here, team T1 has one week in each construction zone to complete its work before moving to the next zone. The next team, T2, follows on at the week-beat interval and the next team follows similarly. Within each construction zone, mechanical and electrical work has various sub-process activities, as does the building fabric works (dry-lining, ceilings, painting, flooring etc.). These tight and dependant relationships are what Thomas et al. (2005) called symbiotic. These relationships exist within this project. Table 1 shows the agreed sequences between each M&E process (MEP 1, 2, 3 etc.), and associated building fabric processes (BFP 1, 2, 3 etc.).

Table 1: Construction Zone Process and Activity Schedule.

PROCESS ID	INSTALLATION ACTIVITY
BFP 1	Thin bed screed, mark out and fit dry lining header track.
MEP 1	High level first fix (rough-in).
BFP 2	Dry-lining studwork and first side dry-lining.
MEP 2	M&E drops within walls.
BFP 3	Second side dry-lining, tape and joint, mist coat painting.
MEP 3	Medical gas pipework, power and control cabling, wall mounted M&E equipment.
BFP 4	Ceiling bulkheads, ceiling grid, service tiles for M&E devices, door frames.
MEP 4	Ceiling mounted M&E equipment.
BFP 5	Vinyl floor, final painting, doorsets and ironmongery, cupboards, fixed furniture.
MEP 5	Final connections to equipment, WC's, baths, door mounted electrical accessories.
BFP 6	Ceiling tiles (excluding commissioning access tiles), carpets and final clean.

Each of these construction processes is interrelated and therefore dependant upon each other to be complete as planned as a precondition. Figure 2 represents a template

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[7] The words team and crew are used in this paper and have the same meaning; a group of skilled and semi-skilled operatives (workers) working together to perform planned operations.

construction zone assembly process, mapped onto an assembly process, as figure 1, Fredriksson (2006).

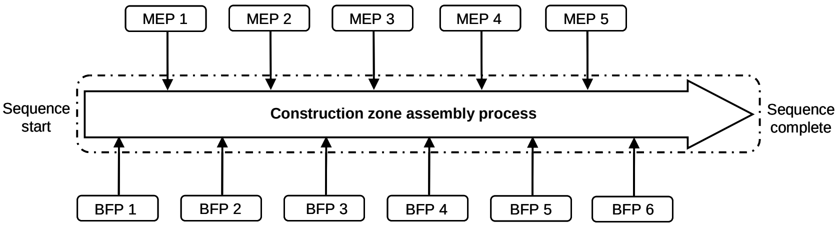

Figure 2: Construction zone assembly process.

This shows the M&E processes (MEP 1-5) and the building fabric process (BFP 1-6). It starts with a designated construction zone made available for work and finishes when all works are complete and ready for commissioning, once adjacent areas and systems are ready. As seen in table 1, each MEP and BFP activity has various sub-processes within it and MEP 1 has been shown in figure 3. MEP 1 consists of at least seven sub-processes, each of these conducted by separate crews. This now shows the outputs of the parts classification team where corridor and riser modules have been incorporated, with the remaining MEP sub-processes being component supplied. MEP 2-5 follow a similar format, with sub-process components and modules being assembled together to form the final M&E systems.

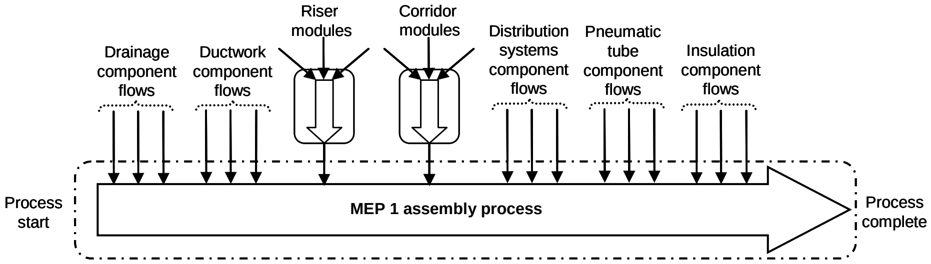

Figure 3: Mechanical and electrical process 1.

A template was developed which sequenced each sub-process commencing with BFP 1, to completing BFP 6 using the week-beat method. Here, each activity was allowed one week to complete its operation before moving on to the next zone, with no other operations being allowed. The calculated cycle-time for this was 50 weeks; however this revealed both overproduction and bottlenecks in the system. Overproduction is a waste to be eliminated in a lean ideal and existed because corridor modules are installed during its week-beat operation, with the distribution systems emanating from it not starting until the following week; this is the waste of overproduction (or unused inventory) according to Womack and Jones (1996). The solution to this was to close-schedule certain operations in the sequence. Close scheduling is a technique used in period batch control (Burbidge 1996) where following operations are started on a batch before the preceding operations have been completed on all the parts in the batch. As a result of this, in MEP 1 the fitting of distribution systems from corridor modules commences the day following the first four modules being installed. The bottlenecks were the requirement for four weeks for each key building fabric process for dry-ling operations BFP 2 and BFP 3, following input in scheduling workshops from the preferred dry-ling contractor stating that one week is not sufficient for the volume of work required. The method used to overcome this was to elevate the bottleneck and to subordinate the following operations to its pace (Goldratt and Cox 2004). Here, four weeks for the bottlenecks BFP 2 and BFP 3 were allowed and their following operations, MEP 2 and MEP 3 are subordinated to their pace. However, in order to maintain the week-beat, a construction zone was further divided into equal quadrants, each approximately 250m², allowing one week per zone quadrant for BFP 2 and 3 operations, with following non-bottleneck processes subordinated to this pace. Construction zones were then close-scheduled a week apart meaning that a new BFP 2 process team will commence in a new construction zone one week after the first zone commences and so on, this also maintains the week-beat. With parallel working of certain MEP sub-process crews (where separated by physical space), the net effect of this sequencing is to reduce the first pass construction zone cycle time from 50 weeks to 39 weeks, a 20% cycle-time reduction. When projecting these agreed sequences with scheduled resources across the project, a 35% reduction in forecasted onsite operatives is achieved. Also, because of the simplification of the assembly process, a lower ratio of skilled to semi-skilled operatives is required, which reduces the average hourly cost of labour. This will further reduce the outturn labour cost of the project.

FLOW OF SPACE

It is understood that crews need space in which to perform their operations without delay. This includes space that is safe and not cluttered with materials or other crews (Winch and North 2006). In the construction system materials for the specific MEP processes will be delivered by a logistics crew to the point of use, in either module form (type A), or parts-kitted on trolleys (type B), with consumables (type C), being replenished into parts trolleys according to use. No surplus parts, other than those planned are allowed on site and are postponed offsite until they are needed. Also, by planning in detail the sequencing of each trade process (MEP and BFP) as described above, the work spaces will be free of other crews operating in the construction zone, this avoids the problems associated with the poor performance of crews with symbiotic relationships (Thomas et al. 2005). The week-beat does allow for more than one trade operation in the same zone, but only where they are physically separated by space. For example corridor modules are installed at the same time as main ductwork runs through rooms, these actions being specifically designed this way because they will not interfere with each other. At any rate, parts for the days work will be in roll cages or trolleys, which are simply pushed out of the way should the need arise to do so. When a team completes its operation in a zone, their work centres go with them, therefore leaving nothing behind. This is a rule in the system.

FLOW OF CREWS

Work is to be conducted on site using a mixture of logistics, specialist trade and composite work crews. Logistics crews are trained general purpose operatives who undertake materials handling, fork-lift driving, scaffold assembly, elevated working platform operation, diamond drilling and waste management. They are also trained banksmen and slingers to off-load materials using site cranes. Installation crews are planned to flow through the system according to the week-beat sequence. For example, the drainage pipework crew in MEP 1 undertake their operation in zone one for a week, before moving to zone two, and then zone three etc. Similarly, the riser module crew and subsequent crews follow the same flow. Using this method, each week long operation requires only one crew to complete all zones. Those operations such as BFP 2 and BFP 3, which have a four week operation, will require three teams in the week beat sequence, each cycling around the zones according to the beat. Composite work crews are used where the installation of components together requires this, such as the pipework and electrical containment distribution systems emanating from corridor modules. Composite pre-assembled brackets support both services and only require the mechanical fixing together of quick-fit components. Plant room equipment and large modules are installed using specialist plant handling crews as these are expensive type A parts that require specialist attention.

As discussed earlier the resources in the system have to be foreseeable and reliable, otherwise it is considered to be fragile. Safety stock and safety lead times are built-in to the supply chain component of the system and here capacity buffers are built-in to the lean site operations. Each week-beat process has a five day slot to complete its operation however the work will take only four days with scheduled resource with the fifth day acting as a capacity buffer. As work proceeds and if buffers are not required, operatives can use this time to make ready for the next operation, or be flexed to do other working backlog operations for that day.

FLOW OF EQUIPMENT

Crews require the right equipment in order to perform their operations according to the week-beat. Of importance though is that whatever equipment or work method employed allows the task to fit the worker and not forcing the worker to fit the task. This method ensures good ergonomics for the worker, which is a principle objective of this project. Tasks in each MEP process have been analysed, with equipment selected to facilitate the operation to be undertaken. This analysis has extended also into the key interfacing BFP processes, such as dry lining. Each crew will be kitted with mobile work cells, which includes work benches; materials (type B) trolleys; consumables (type C) parts trolleys; electro/mechanical lifting gear; ergonomic access equipment (Court et al. 2005); appropriate tools; task lighting and waste bins. This equipment is provided to all crews, even if they are sub-contracted, as each worker has the same right to good ergonomics. The company will benefit from the provision of this equipment in terms of improved health, safety and productivity, irrespective of the cost of doing so. This is an investment in the well-being of the worker as well as the project itself.

EXTERNAL CONDITIONS

External conditions, such as the weather have been considered in the construction system. M&E assembly work commences from the lower building levels and flows upwards in the same sequence as the concrete frame. The building envelope is fitted as the concrete frame progresses upwards and rainwater pipes are fitted with this envelope to drain any rainwater away during construction. Assembly operations commence in construction zones when the structure is watertight, thereby avoiding any likely disruption from adverse weather conditions.

CONCLUSIONS

This paper has described the design of the lean site operations component of the construction system. When combined with its supply chain component forecasted onsite labour is reduced by 35% together with a 20% reduction in construction zone cycle-time. This is achieved by managing the seven precondition flows of Construction Physics and how these interact with each other in the construction system. This reduced onsite labour means less workers are exposed to health and safety risks from construction operations. By using modular assembly techniques with ergonomic workplace design an improved quality of work is provided for those workers that are required on site, carrying out simpler assembly tasks as a result of the construction system. Productivity gains will be realised by the system acting as an antidote to the waste that traditionally occurs in M&E construction which causes labour cost escalation, as reported in Court et al. (2005). The labour cost centre budgets should therefore be achieved by avoiding this waste. This will be tested in the implementation phase on the case study project. Finally, the authors believe that the system in operation constitutes a modern process of assembly.

FURTHER RESEARCH

Further research is currently being conducted to finalise the design of the supply chain component of the construction system and together with the lean site operations component will be applied in practice on the case study project, this being the final phase of research. The results emerging from this will be reported in future research papers.

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