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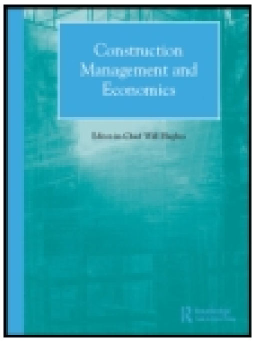

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What constitutes good production flow in construction?

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The notion of production flow is not well understood in the context of construction. A coherent, consistent theoretical model of flow would have practical value as it would support development of better approaches to managing production within and across projects and of measures of flow quality needed to implement them. A literature review and analysis of existing conceptualizations of flow in manufacturing and in construction lead to formulation of a model of construction flow that has three interrelated but distinct axes: project portfolio, process and operations flows. A tentative set of ideal conditions for good flow was formulated with regard to each of these three primary flows. The review, the summary model and the set of conditions provide a basis for further research and development of a comprehensive model of flow in construction and a definition of what constitutes good flow.

Keywords: Construction process, lean construction, lean production, production process, work flow.

Introduction

What constitutes good production flow in construction? Although apparently a simple and straightforward question, many project managers, site supervisors and subcontractors struggle to define a precise response. The difficulty arises because most construction professionals lack a clear understanding of the concept of production flow per se and because what constitutes '*good*' flow is subjective and dependent on the utility of the person being asked. As Koskela pointed out, the 'Transformation' view of production in construction is predominant and the 'Flow' view is absent from traditional construction management training and practice (Koskela, 2000).

The economic motivations of the different actors in construction are at best misaligned and in many cases in direct contradiction (Fenn *et al.*, 1997). The economic driver for any company or individual is to increase well-being by maximizing its own real income (Saari, 2011). Yet under the most common commercial relationships, established by lowest price tendering, companies allocate resources in uncertain conditions according to lose–lose equilibria with suboptimal outcomes (Sacks and Harel, 2006) due to their divergent views of what constitutes good flow.

In addition, it is difficult to measure flow. Rooke *et al.*, (2007) identified the difficulty that arises due to the fundamentally different ways in which people understand 'atemporal substance' vs. 'temporal process'. Using examples from quantity surveying and structural engineering, they posit that civil engineers are predisposed to understand construction better in terms of the end product rather than the process. This leads to the use of strategies and tools for construction project control based on traditional tools, such as the earned-value method. The method measures work done, but does not reveal anything about the quality of the flow (Kim and Ballard, 2000).

Establishing a coherent, consistent and broadly acceptable definition or model of good work flow in construction is therefore essential to establishing common ground and for development of useful tools for holistic improvement in the industry. But before attempting to define *good* flow, we must define production flow itself in the context of construction. In construction management literature and practice, the term '*flow*' is used broadly and generally to refer

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to something akin to the flow of production in manufacturing (e.g. Arashpour and Arashpour, 2015; Ballard *et al.*, 2003; Brodetskaia *et al.*, 2011; Hamzeh, 2009; Jongeling *et al.*, 2008). Kalsaas and Bølviken (2010) explain that the dictionary definition of flow as a 'continuous stream of something' adequately describes the way in which the term as been used in many discussions in the Lean Construction literature. This definition of the term 'flow' is not necessarily precise but it has some intuitive characteristics and it has become popular among both practitioners and academics (Kalsaas and Bølviken, 2010). Intuition, however, is not sufficient for achieving a common understanding as a basis for action, nor for compiling metrics of work flow and nor for managing production.

The goal of this review, therefore, is to set the stage for construction management researchers and practitioners to engage in research, debate and development towards a useful theoretical model of flow in construction. The research comprises three steps: a literature review and discussion to establish the state of the art; proposition of a candidate 'Portfolio, Process and Operations' model of flow in construction; and synthesis of a set of conditions for good flow that represent an initial working proposal. All three are informed and influenced by the bodies of the literature on flow in manufacturing, lean production, lean construction and project control in construction management.

The paper has three parts that correspond to the three steps outlined above. The first part consists of the next two sections, titled 'Flow in Manufacturing' and 'Flow in Construction'. These sections provide the background concepts of production flow in manufacturing and discuss the current understanding of production in construction. The second and third parts are presented in sections titled the 'Portfolio, Process and Operations Model' and 'What Constitutes Good Flow in Construction?', respectively. The conclusion section summarizes the model, discusses its practical implications, as well as its limitations, and reinforces the argument for development of a broadly acceptable conceptual model of production flow in construction.

Flow in manufacturing

The concept of flow in manufacturing is well defined. It is understood as a path through which a product progresses as it is processed from raw material to finished product (taking flow as a noun) or as the physical movement of the product along the path (as a verb). The flow path is called the 'value stream', and the actions performed along it can be classified as value adding and non-value adding actions (Rother *et al.*, 2003 p. 3). In lean production terms, good flow is understood to be flow in which the value stream has the minimum possible non-value adding actions, i.e. the minimum possible waste (Womack and Jones, 2003).

In more general terms, 'flow production' – synonymous with 'continuous production' – is 'a manufacturing process in which finished products are made from basic materials in one continuous process without interruption' (Cambridge Business English Dictionary, 2015). This stands in contrast to manufacture of discrete products, or 'batch production', in which products move between operations in batches. Both definitions refer to the flow of products through a production process that consists of operations. The distinction between the two lies in the continuity or otherwise of the flow from the point of view of the product, which may be continuous (such as a liquid in a pipe) or discrete (distinct products that may flow as single pieces or in batches). If there is no waiting between operations, discrete single-piece flow may be considered to behave like continuous flow.

The notion of flow in production is predicated on the idea that the value stream as a whole can be subdivided into a sequence of tasks between which the product moves. This subdivision, or 'decomposition', found economic justification in the work of Adam Smith and later economists (up to the early nineteenth century) and is reflected in the specialisation of workers in production tasks. Charles Babbage, for example, considered the division of labour to be essential, and not only for the reasons of direct productivity increase, which is obtained through expertise and learning of a simple process. He saw in the very nature of manufacturing – and in the way specialized factories were organized in the broader economy – that the manufacturer could for the first time buy only the exact amount needed of any given input. In this sense, they could buy the product, without paying for the 'downtime' cost of the service. As quoted by Norton Wise (1989) and by Lewis (2007), Babbage explained that (Babbage, 1832 pp. 175–6):

> ..the master manufacturer by dividing the work to be executed into different processes, each requiring different degrees of skill or of force can purchase exactly that precise quantity of both which is necessary for each process; whereas, if the whole work were to be executed by one workman, that person must possess sufficient skill to perform the most difficult, and sufficient strength to execute the most laborious of the operations into which the art is divided

This suggests that the waste of suboptimal exploitation of a resource can be removed from the system, provided only that the system is designed so that each resource performs only the work it is designed for and that the flow of work is balanced to provide continuous occupation of the resources.

However, simple decomposition of this kind leads to the mistaken notion that optimization of the parts of a process leads to optimization of the whole. Henry Ford and other manufacturers in the automobile industry at the start of the twentieth century considered an additional view, that of the flow of the whole process. Their understanding of production flow finds direct expression in the production systems they devised. The guiding principle of Ford's manufacturing system was constant motion of the product (Ford and Crowther, 1926):

> Work is planned on the drawing board and the operations sub - divided so that each man and each machine do only one thing ... the thing is to keep everything in motion and take the work to the man not the man to the work. That is the real principle of our production, and conveyors are only one of many means to an end.

Frank G. Woollard was an early pioneer of flow production systems, well before Taichi Ohno developed the system we recognise today as lean production. His approach was conceived during the First World War and applied more fully in the 1920s in the UK at the Morris motor car manufacturing company (Emiliani and Seymour, 2011; Woollard and Morris, 1925). Woollard stated eighteen principles for flow production systems, among them '*Processing must be progressive and continuous*' (#8) and '*A time cycle must be set and maintained*' (#9).

Process flow and operations flow

In manufacturing, Shingo emphasized the differences between two axes of flow: *process flow*, which represents the progress of a product along a production line, and *operations flow*, which represents the individual actions performed on the product at any given workstation (Shingo and Dillon, 1989) (see Figure 1):

> When we look at process, we see a flow of material in time and space; its transformation from raw material to semi-processed component to finished product. When we look at operations, on the other hand, we see the work performed to accomplish this transformation — the interaction and flow of equipment and operators in time and space. Process analysis examines the flow of material or product; operation analysis examines the work performed on products by worker and machine.

This is a fundamental distinction and enables focus on improvement of the flow of product (process flow) on

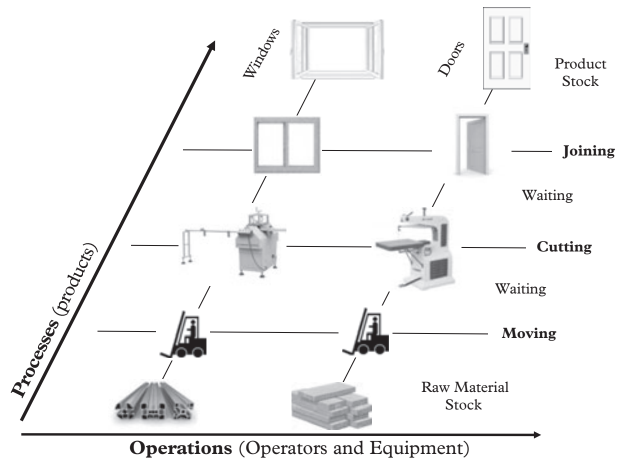

Figure 1 Operations and processes in manufacturing, based on 'The Structure of Production' by Shingo and Dillon (1989)

the one hand and on improvement of operations on the other. Process is improved by removing, as far as possible, non-value adding steps such as moving, waiting and inspection, and by minimising set-up times and rework. Operations are improved by balancing the work of operators, improvements to methods and tools, etc.

> To make fundamental improvement in the production process, we must distinguish product flow (process) from work flow (operation) and analyse them separately…

Viewing a production process as a single line that includes the operations leads to

> the mistaken assumption that improving individual operations will improve the overall efficiency of the process flow of which they are a part. (Shingo and Dillon, 1989 p. 4)

Factory physics

Shingo's analysis, the Theory of Swift, Even Flow (Schmenner and Swink, 1998) and the logic of the Theory of Constraints (Goldratt, 1997) all provide sound advice for designing and operating manufacturing plants. However, they are descriptive in nature and thus do not provide any way of making quantitative assessments of the potential impact of any change to production system design or to flow control. Identifying the lack of a quantitative model, Hopp and Spearman (1996) presented a rigorous approach to the definition of the behaviour of production systems under various conditions, resulting in a set of predictive relationships.

The relationships, expressed using formulae such as Little's Law[1] (Little and Graves 2008), enable engineers to determine the quantitative boundaries of performance they can expect from the production systems they design and manage. The parameters that influence performance include the feeding rates, bottleneck rate, variability of production rates, the structure of the line, batch sizes, availability of equipment and of labour, variability in customer demand and production flow control policy. Policies considered include push, controlled work in progress (CONWIP) and pull. The throughput, the size of buffers (time, product or capacity), the work in progress (WIP) and the cycle times that result from any given set of parameter values can be estimated. In particular, short cycle times and low levels of WIP are considered to be qualities of systems with good flow.

Re-entrant flow

Re-entrant flow occurs when a product is required to return to a workstation in which it has already been processed earlier in its manufacturing process (Kumar, 1993). This may occur by design or in situations where defects identified downstream lead to repeat operations. Re-entrant flow patterns are typical for the semiconductor manufacturing process, where multilayer semiconductor wafers return several times to the same workstation for creation of successive layers (Odrey *et al.*, 2001).

Production control for systems with re-entrant flow poses a number of challenges, because products often pass through the bottleneck multiple times before completion. This is even more complex when there is a mix of product designs, with each requiring different numbers of returns. A wide variety of decision methods have been employed for product routing in real time. Heuristic dispatching rules have strong advantages over more computationally demanding methods in that they are easy to understand, easy to apply and provide rapid response (El-Khouly *et al.*, 2011).

Flow in construction

To complete the background review, we turn now to the current understanding of 'construction flow'. Surprisingly, the term is not well defined. The difficulty arises because of the fundamental difference between the flow of products through a production line in a manufacturing plant, as opposed to the flow of trade crews through the spaces in a construction site. The primary visible flow in the former is of product, while workers are located at their fixed workstations; the primary visible flow in the latter is of workers and their equipment, while the construction product does not move. Intrinsically, the 'work', in as far as it is understood to represent the product in the manufacturing world, does not 'flow' through space in the construction world (although the work does flow through time). So what then do researchers and practitioners mean when they refer to 'flow' or to 'work flow' in the context of construction?

Positioning construction on the product–process matrix

The product–process matrix is a framework for defining alternative business and production strategies (Hayes and Wheelwright, 1979). It posits that all manufactured products lie on (or near) a diagonal line in a two-dimensional matrix defined by an axis of product structure (low-volume to high-volume products) and an axis of process structure (from jumbled 'job-shop' flow to continuous flow). Schmenner (1993) adapted the matrix to plot production systems instead of products[2], as shown in Figure 2.

Where does construction production fall within the product–process matrix? Construction is commonly seen as project-based production with one-of-a-kind products, which places it in the upper left corner and therefore implies a 'very jumbled flow; process segments loosely linked'. Indeed, empirical evidence from measurements of the flow of crews through locations in traditionally managed construction projects, such as those presented by Seppänen (2009), tends to support this view. The flows are jumbled, and within each location, the process segments are indeed loosely linked with extensive periods between operations in each location. The buffer of unfinished products between the operations of successive trade crews in a building can be easily discerned in a flow-line chart (see Figure 3). It can be measured in space (number of empty spaces, measured vertically) or in time (waiting time between operations, measured horizontally).

Yet this view of construction as project-based production with one-of-a-kind products and 'very jumbled flow' is narrow and to a certain extent a self-fulfilling prophecy. According to the process view, a construction project is composed of distinct spaces, with varying degrees of similarity between them. In this view, construction production may be considered to be batch flow or line flow. According to the operations view, i.e. the multi-project view of a subcontractor, line flow is apparent – the subcontractor produces a high volume of relatively similar products in its operation. Given that managing flow is more difficult for more varied product mixes and therefore easier towards the bottom

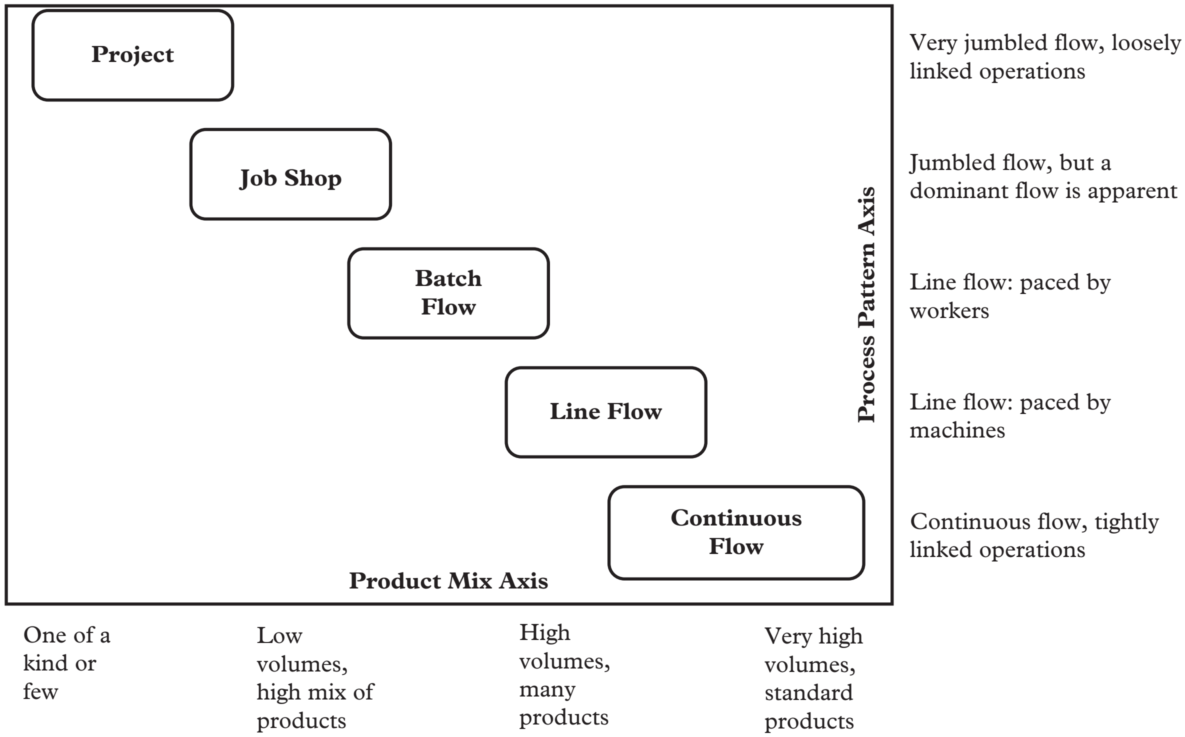

Figure 2 Types of production systems, based on the process pattern/product mix matrix (Schmenner 1993)

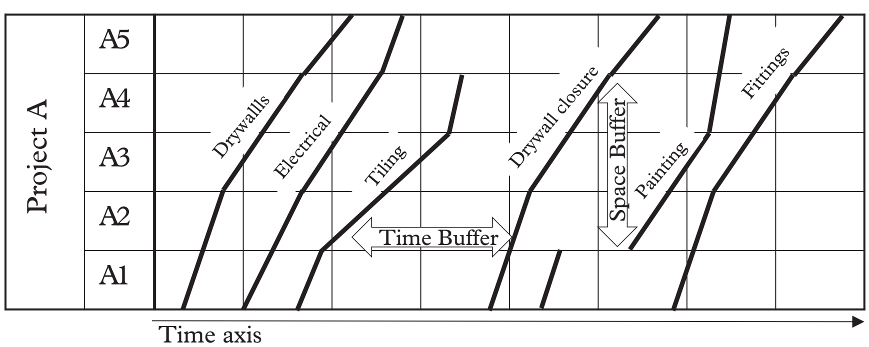

Figure 3 Buffers of space and time illustrated in construction project flow-line charts

right of the matrix (Figure 2), production control naturally defaults to the operations view, i.e. production is left to the subcontractors to manage as best they can when general contractors neglect their responsibility for production control. Under these conditions, subcontractors have a direct interest in productivity outcomes, whereas general contractors have little or no interest in the productivity outcomes as they are buying products (such as a unit area of completed tiling) at fixed prices.

Another important observation is that a construction project is not homogeneous in terms of its product–process mix. First, as distinct from manufacturing, the work in a construction project includes establishing the production facility (i.e. 'building the factory') on-site, where no production facility existed before, and progressively dismantling the facility as the project winds down. This typically includes set-up of cranes, concrete formwork, scaffolding, stores, fencing, offices, etc.

Second, the various parts of a building are different in nature and so are the processes through which they are built. Structural work has a fixed sequence of locations that is dictated by technological constraints because earlier parts support later parts. Building systems (mechanical, electrical, plumbing) do not have fixed technological dependence between their locations, nor do interior finishing works. Exterior envelope works may be part of the structure or they may be independent of it in terms of construction sequence. Each of these (structure, systems, finishes and exterior) may therefore be classified into different classes on the product–process matrix. The implication is that their production flows are also different, and therefore, the interfaces between them often exhibit significant buffers of time and/or space.[3]

Lean construction view of work flow

Koskela (2000) challenged the narrow thinking embodied in the dominant 'transformation' view of production in construction, proposing an integrated transformation, flow and value view (TFV). The primary conceptual source for the flow view is Shingo's distinction between process and operation. Transformation corresponds to operations, flow to process. In the context of construction, Koskela *et al.*, (2007 p. 216) distinguish between operations, referring to the individual tasks performed by crews and represented in activity networks, and process, referring to the flow of work (construction products). They explicitly refer to the latter as 'work flow'.[4]

In the glossary of Ballard's (2000) seminal thesis on the Last Planner® System (LPS), work flow is defined as '*the movement of information and materials through a network of production units, each of which processes them before releasing to those downstream*.' This definition is fine for a factory, but appears to be inconsistent with the intended meaning in the context of the LPS. Work flow management in the LPS deals with 'assignments' which are directives to production units (teams or crews) that encapsulate the work of the production unit in a specific location performing a defined work method using information and consuming materials. With the exception of modular and/or prefabricated construction, the products of construction do not move, which implies that the movement of materials in Ballard's definition relates to raw materials. The implied definition of work flow as movement of information and raw materials appears inadequate, failing to capture the metaphorical flow of the product.

From these definitions, we can see that 'work flow' in the lean construction literature refers to the flow of 'work packages'. Work packages encapsulate crew, product, work method, design information and equipment. Ballard, for example, explains this view in a passage titled 'Learning to see work flow' (Ballard, 2005):

> Our initial thinking about production control in construction was based implicitly on the idea of reducing delays in craftworker activities, and thus increasing labor utilization and productivity. Once we started experimenting on projects, and with the advantage of early understanding of the Toyota Production System, we realized that work flow reliability was the proper concept and that reliable work flow impacts the productivity of downstream players. That impact is more important than the improvement in productivity of any single player. This completed the shift in focus from productivity and resource utilization to work flow as the instrumental cause for performance improvement, and the shift from the operation or crew to the project (or even multiple projects) as the ultimate object of improvement efforts.

The project is the object [of improvement efforts], but the notion of a physical 'product' as a component of the project is not mentioned. The idea of a physical location as a distinct physical product is absent from this definition of work flow.

Location-based planning and control

Kenley and Seppänen (2009) suggested that the construction metaphor for product flow is the flow of locations, which although they do not move are analogous to the products moving down a production line, onto which incoming parts and materials are assembled in the operations performed by trade crews. In the same way, as the physical flow of products passing a machine in a manufacturing plant can be seen by a stationary observer, the relative flow of locations can be seen in a video recording from a camera carried by a construction worker. This can therefore be understood to be the primary construction product flow.

The metaphor of locations as products requires elaboration. Locations within a building are not singly defined, but rather are suited to each trade. A single room may be useful as the unit of analysis for one trade, whereas a whole apartment, or a façade, may be appropriate for other trades. The sizes of locations can also be varied to adjust work content for levelling operation durations using line-of-balance planning (Pe'er, 1974). Locations are also aggregated into higher order locations, in much the way that sub-assemblies are aggregated into higher order assemblies in manufacturing. An implication of the elasticity of locations and therefore of work package sizes is that the takt time is slightly different in construction from its standard definition in production (the available production time in a given period divided by the number of products required by customers in that period). In construction, the number of locations decided upon in production planning determines the takt time. It is not fixed by an immutable number of products.

An additional distinction is that the sequence of location products between operations is fixed for the case of structural works, unlike manufactured products where the sequence of individual products can be changed in between operations (if for instance a defect is identified). The sequence of operations in interior and finishing works is not constrained in this way.

Another anomalous consequence of the location flow view is that it is possible for more than one trade crew to work in a single location at a time. This phenomenon has been called 'stacking of trades' (McDonald and Zack 2004 p. 4) and 'workstation congestion' (Koskela, 2000, p. 189), and it generally reduces productivity. It is analogous to the imaginary scenario of multiple machines working simultaneously on a single part in a manufacturing plant.

Thus, Kenley and Seppänen (2009) implicitly define their view of construction work flow through their rejection of activity-based scheduling in favour of location-based scheduling (p. 5), emphasising locations as a construction embodiment of a product that flows through a set of production operations. Yet they do not define optimal work flow, sufficing with the more general statement that 'An optimal control action plan is that plan which will deliver the optimum outcome for the project overall' (p. 354). They do not say what that 'optimal overall outcome' is, for whom it is optimal, nor how it can be measured. They do, however, define characteristics of bad work flow, which include breaking the work flow such that the work of the succeeding trade is discontinuous, changing the sequence of locations from the planned sequence, and overlapping production [of the same task] in multiple locations. These are useful, although they mix process and operations views: breaking the work flow refers to the operations axis, whereas changing the sequence of locations and overlapping production refer to the process axis.

Re-entrant flow in construction

In the most common on-site building construction methods, re-entrant flow is the rule rather than the exception. It occurs when a trade is required to return to the same work space for different process stages. In residential and commercial construction, for example, the return of drywall, plumbing, electrical and other trades multiple times to the same location is an inherent feature of the construction method (Brodetskaia *et al.*, 2013)[5]. A value stream map for a typical residential apartment revealed as many as 44 handovers from one team to another (Sacks and Goldin, 2007) with only 18 trades, reflecting multiple cycles of re-entrant flow. Rework to correct defects, to revise work performed prematurely due to 'push' control, or as a result of late design changes is an additional, unplanned but common source of re-entrant flow patterns in construction.

Re-entrance poses an interesting and important challenge in allocating resources: in order to prevent 'starvation' of the subsequent trades, the crews of a trade with re-entrant work flows should be effectively shared between operations that 'open up' new locations for work and operations that 'close out' other locations. Where the necessary increase in resources for the re-entrant trade is not provided as their second and later operations commence, then not only will the other trades experience discontinuous work, but the subsequent locations will also suffer extended cycle times. Although re-entrance is primarily a phenomenon of the process axis, extending cycle times for locations, it also impacts the operations axis (causing discontinuous work and increasing set-up times).

Construction physics

Bertelsen *et al.*, (2006) introduced 'Construction Physics' as a comprehensive way of understanding the construction process from a flow perspective. Under the subheading 'Flow in Construction' the paper states (Bertelsen *et al.*, 2006, p. 33):

> Construction Physics is a theory based understanding of the nature of the flows and their interactions in the construction process. The flows comprise physical flows in the traditional sense, such as flow of materials and equipment, but also immaterial flows such as flow of information, crew, space and external conditions (weather, authorities' approvals, etc.). In short: 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. Construction Physics also looks at the interaction between the flows such as how the flow of materials influences the flow of space.

Construction Physics draws inspiration from Hopp and Spearman's 'Factory Physics' (Hopp and Spearman, 1996) to emphasize the flow world view in addition to the traditional material or task-based conception of flow in construction. It emphasizes the seven prerequisite 'feeder' flows that it classifies rather than the flow of 'locations' as product flow. As can be seen in the quote above, it defines 'space' (space in a building in which work can be performed) as a prerequisite resource or 'feeder' flow. The flow of 'locations' that represent construction products, on the other hand, as defined by

Kenley and Seppänen, (2009) is conceptually different. Physical spaces must be considered to flow both as prerequisite places for some production operation to be performed in (the process view), as well as in the form of representations of products or sub-assemblies (the product view).

Impact of subcontracting

Subcontracting is an aspect of the construction industry that has a profound impact on the nature of its flows and the ability of construction managers to control work flow. Its prevalence has been documented in numerous studies (Hinze and Tracey, 1994, Hsieh 1998). In the US, a 1998–1999 study of general contractors in commercial construction found that 90.9% of the trades were subcontracted more than 75% of the time (Costantino and Pietroforte, 2002). Subcontracting results primarily from the economic imperatives of reducing risk inherent in maintaining a directly employed workforce that must be employed in a portfolio of contracts that may grow or shrink with the vagaries of the economy. Additional factors include trade specialisation (which requires long-term investment in personnel and equipment) and transfer of liability as general contractors transfer risk to subcontractors.

The most important implication of the prevalence of subcontracting is that construction contractors manage contracts rather than production. As Ball observed already in 1988 (Ball, 2014):

> To summarize the shift in the role of the building contractor, it is perhaps best to see the change as one of contractors no longer being concerned with production management, which in its direct form is now often the prerogative of the subcontractor; instead, they are increasingly project managers.

Economic game theory models show that the reliability of a project's short-term production plan strongly influences the resource allocations of subcontractors to projects because their perception of the risk of low productivity is directly related to the quality of the information they have concerning the project's production status (Sacks and Harel, 2006). Unreliable production schedules lead to defensive behaviour in which subcontractors allow buffers of locations or time to accumulate before committing resources. Insufficient or late supply of resources in turn increases the instability of the plan. These phenomena can result in variability in production rates and highly varying waiting times between operations, thus negatively impacting the process flow.

Flow of prefabricated or pre-assembled components

Where subsidiary engineered-to-order parts are fabricated and/or pre-assembled, as in precast concrete, steel construction or preparation of modular MEP units, the flow of the interim assemblies is comparable to that of products in a manufacturing process. However, from the point of view of the construction process on-site, they can be considered equivalent to the flow of materials. Although they may have specific designated locations, they are not part of the flow of locations per se.

Location flow and trade flow

In summary, the term construction work flow appears to be used by different authors, and presumably also by practitioners, for what are two distinct flows: 'work' as product and 'work' as task. A preferable approach is to define work flow distinctly according to the two axes of operations and process as *location flow*[6] (process) and *trade flow* (operations), respectively. Whenever the term 'work flow' is used in the context of construction, the need arises to clarify whether the intended meaning is location flow, with the prefix 'work' implying the noun (product), or trade flow, with the prefix implying the verb (operation).

Portfolio, process and operations model

Shingo's conceptual contribution was in recognising that process and operation do not lie on the same axis, but lie on intersecting axes that form a production network (Shingo and Dillon, 1989). Operations are not simply fine-grained aspects of processes, they are different in nature. In this, the second of the three main parts of the paper, a three-dimensional view of production in construction, is proposed, with the addition of a third axis that represents the flow of work from project to project in a portfolio.

Inversion of physical flow on the process and operation axes

The most obvious observation concerning construction location and trade flows is that the process and operations axes are inverted in terms of physical flow. Henry Ford wrote that 'the thing is to keep everything in motion and take the work to the man and not the man to the work' (Ford and Crowther, 1926). In construction, this can be achieved to some extent by moving as much of the production as possible and practical to off-site prefabrication. Yet the work that remains on-site requires the diametric opposite of Ford's injunction: people and equipment are required to move to the work, which remains stationary.

In this metaphor, 'Takt Time Planning' (Frandson *et al.*, 2013; Linnik and Berghede, 2013) is analogous to placing the trade crews on an imaginary conveyor belt, moving at a fixed rate and delivering the crews to the work locations. Line-of-balance scheduling as proposed by Pe'er, (1974) has a similar goal: he expressed the view that construction planning must begin by determining a critical operation, and then aligning all other operations with that one, leading to a 'line-of-balance'-type schedule in which all operations become critical, or near critical, by design.

There are numerous additional differences between factory production and site production. Dos Santos lists sixteen (dos Santos, 1999 p. 40–43), three of which are most significant to the discussion of construction flow. The first is the spatial fixity vs. physical flow distinction made in the previous paragraph. The second is the nature of production on-site in temporary workplace conditions, which is a direct result of the spatial fixity. The third concerns the predominance of subcontracting, discussed in the previous section.

However, there is one more feature that is central to this discussion: construction produces a *project* (e.g. a building) which is an *aggregated* product. Whereas manufacturing delivers individual products that can be consumed one at a time, construction projects are usually delivered as a whole. The spaces of a building (such as apartments, classrooms, hotel rooms) or the sections of a road (bridges, lanes, ramps) are the units of production in construction that are the equivalent of the products that flow in Shingo's definition of process. These part products can only function fully once the whole is complete. A manufacturing process produces an individual artefact, a construction process produces locations, and a construction project produces an artefact that is an aggregation of locations.

Portfolio, process and operations (PPO) model of production in construction

Thus, construction work flow can be understood as functioning on three interrelated axes: portfolio, process and operation. In this model, trade crews are considered to flow not only from location to location within a project, but also from location to location across projects. Operations can extend across projects, reflecting an interdependence between projects.

Figure 4 depicts the PPO model graphically. In standard line-of-balance charts (such as Figure 3), locations are plotted as horizontal strips and the progress of trade crews through the locations is shown

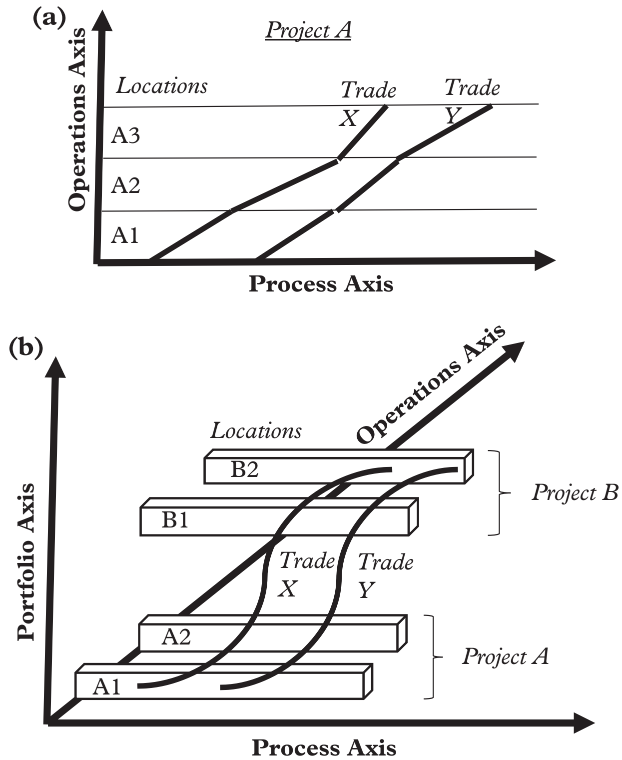

Figure 4 (a) Processes and operations of a single project represented as a two-dimensional space. This is the same as a line-of-balance chart; (b) three-dimensional portfolio, process and operations (PPO) model of construction flows

using inclined lines that represent the crews' flow through the locations as time advances from left to right. Figure 4(a) shows the process and operations plane of the PPO model using the same format as a line-of-balance chart. In Figure 4(b), the process–operations plane is shown as a horizontal plane in a three-dimensional space, with a vertical axis added to represent the portfolio, which can contain multiple projects. The figure illustrates that in the PPO model, trade crews progress in time not only within the locations of a single project, but also across projects.

Figure 4(a) Processes and operations of a single project represented as a two-dimensional space. This is the same as a line-of-balance chart; (b) three-dimensional portfolio, process and operations (PPO) model of construction flows.

Table 1 lists aspects of the three axes that are commonly observed in construction projects. For example, the primary management functions on-site reflect the three axes:

- The *project manager* is concerned with delivery of the project as a whole, uses critical path planning to set milestones and operates through contracts with subcontractors and suppliers;

Table 1 Aspects of the portfolio, process and operations axes in construction

Aspect	Portfolio axis	Process axis	Operations axis
Flow object	Project/building	Location	Trade crew
Cycle time for flow of a single object	Full project duration	Start of structural work to delivery to client	From first to last day of a crew's work on a project
Optimization targets	Project duration and cost	Flow of locations, reduction of WIP, minimum cycle times, quality	Flow of trade crews in and between locations, continuous work, productivity, safety
Management function	Project manager	Works manager or superintendent	Subcontractor, trade crew leader
Planning and control tools	Critical path method (CPM); contracts	Location-based planning; Last Planner® System (LPS)	Operator balance charts; standardized operations; LPS
Symptom/ sign of waste	Budget overrun and/or schedule overrun identified using 'Earned Value' measures; defects	Unoccupied spaces (spaces with no work in progress); crews absent from site; delayed materials; delayed design information; rework	Idle crews on-site; crews waiting for work; small work completion packages; rework
Tactical approach	Contract negotiations, bonuses and fines	Build excess capacity; coordinate across trades	Allow buffers of locations to accumulate before assigning resources, understaffing
Scope of planning and control	Single project	Work or product type (e.g. structure, building systems, interior finishes)	Operations (specialized trade work)

- The *works manager (*site superintendent) manages the process, focusing on advancing work to complete the spaces within the project. The works manager uses production control methods such as the Last Planner® System and tends to build buffers of capacity and materials to ensure continuous work in the locations;
- The *subcontractor trade crew leaders*[7] (operations manager) try to ensure high productivity through continuous employment, often by evaluating the scope of work likely to be made ready across multiple projects and by allowing buffers of locations ready for their trade to accumulate.

The flow of trade crews between projects is distinct from the flow of trade crews within a construction site. This distinction is similar to that between activity management (i.e. operations) and resource management apparent in the GRAI model (Doumeingts *et al.*, 1995), which explicitly defines the function and tools for it, such as resource allocation planning. The signs of waste for these flows are unallocated (and therefore idle) resources. The tactical approaches to avoid this waste include 'overbooking' (i.e. commitment to allocation of resources to multiple projects beyond their ability to supply simultaneously), which is common among trade subcontractors and design firms.

Interdependence between projects in the PPO model

Addition of the project portfolio axis reflects the fact that design and construction occur simultaneously across many projects in any given regional economy. Unlike neighbouring factories, each of which have their own and essentially independent production resources, construction projects in any given economic region are codependent on the same subcontractors and their labour (Bertelsen and Sacks, 2007). Subcontractors balance their workload across projects, creating a flow of labour between the operations of different projects. As shown in Figure 5, a trade subcontractor will attempt to achieve unbroken utilisation of its crews, even if this requires shifting between projects from week to week or from day to day, resulting in discontinuous location flow from the project perspective. Designers do the same thing, with the result that the flow of product information (drawings or models) is commonly also discontinuous and unstable from the project point of view (Tribelsky and Sacks, 2011). In this view, continuity of trade flow can be said to be achieved at the expense of location flow.

This balancing of load across projects by suppliers means that the common understanding of the relationship between portfolio, process and operations as a linear

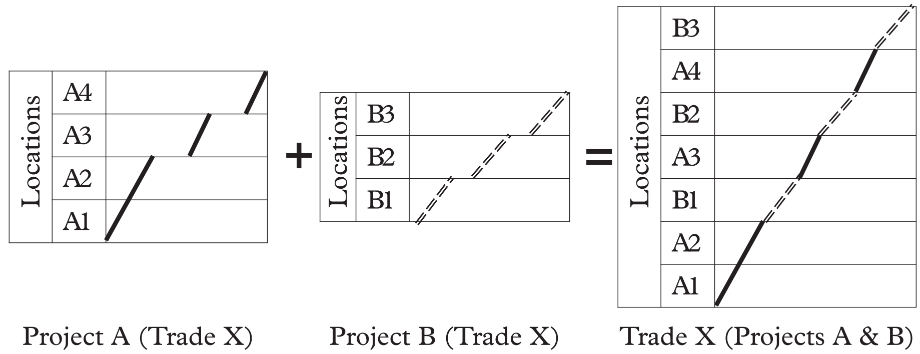

Figure 5 Trade X works on two projects: A and B. Trade X has continuous work, but both projects A and B experience interruptions. This results in discontinuous location flows within projects although there is continuous trade flow across projects

hierarchy, as shown on the left-hand side of Figure 6, is insufficient because it reflects a project-centric world view in which resources are dedicated to projects. The right-hand side of Figure 6 correctly reflects the cyclical nature of this relationship.

Where multiple projects are managed by a single construction company or owner, the collection of projects can be termed the company's 'portfolio' of projects (see Figure 6). Adding the axis of a portfolio of projects has the benefit of focusing attention on the fact that a company or an owner can consider the flow of projects in a portfolio in much the same way as one considers the flow of products in a production line. There are clear and apparent economic benefits to keeping the cycle times of projects as short as possible, and applying Little's Law, this means that the number of projects operated in parallel should also be controlled. Where a company plans a certain throughput level, new projects should only be started when the capacity of its own resources and that of regional subcontractor resources allows.

However, in free market economies without centralised control, market forces regulate supply of resources and thus regulate the cycle times for projects. Subcontractors perform work for multiple general contractors across an economic region, encompassing the portfolios of multiple companies. Opportunistic behaviour on the part of subcontractors as they shift resources from project to project introduces instability that restricts project managers' abilities to plan ahead. This reflects an interdependence between operations and projects, so that the ends of the linear hierarchy must be joined in a cyclical dependency relationship. This is the intent of the right-hand side of Figure 6.

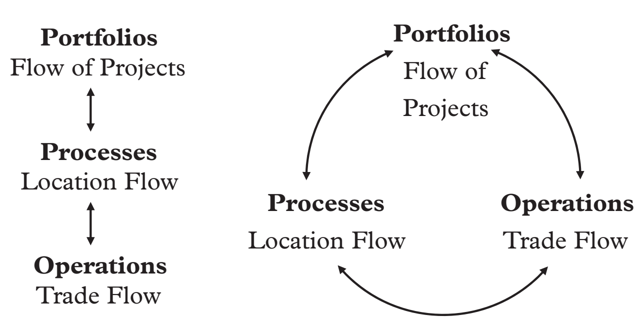

Figure 6 Hierarchical vs. cyclical view of the relationship between project portfolios, processes and operations

What constitutes good flow in construction?

This section, the third of the three main parts of the paper, draws on the basic principles for good production flow as defined in the literature to compile a candidate set of prescriptive conditions for good flow according to the framework of the PPO model.

A working set of conditions for good flow in construction

Broadening the view to consider all three aspects of flow (project flow, location flow and trade flow), a set of ideal conditions is proposed as a benchmark statement of optimal construction flow. The conditions are listed in the first column of Table 2. The second column of Table 2 provides the production flow principle on which the corresponding condition is based, with reference to the literature.

Among the key sources for the principles underlying this set:

- Koskela, (2000) defined six principles for improving flow in production processes: reduce waste (including waiting time), reduce cycle time, reduce variability, minimise the number of steps, maximise flexibility and provide transparency. Koskela emphasized reduction of cycle time, stating that

Table 2 A working set of conditions for good flow in construction according to the PPO model

Optimal flow conditions	Production flow principle
1. Project portfolio conditions (project flow)	
1.1. The cycle time for all projects is minimized.	Minimum cycle time; Little's Law (Hopp and Spearman 1996; Little and Graves 2008)
1.2. The work-in-progress inventory in a company's portfolio is kept to a minimum.	Minimum WIP inventory (Hopp and Spearman 1996; Ohno 1988)
1.3. The batch size, measured as the number of distinct projects managed by the same management team, is one.	Single-piece flow (Womack and Jones 2003)
1.4. Projects move from development to construction at the last responsible moment, in response to pull from customers.	Pull flow (Womack and Jones 2003)
2. Process conditions (location flow)	
2.1. Balanced work: the variation of takt time across locations for all trades, measured as the standard deviation of the average number of locations completed per unit of time for each trade, is zero.	Takt time variation (Emiliani and Seymour 2011, Schmenner and Swink 1998, Woollard and Morris 1925)
2.2. The batch size, measured as the number of locations occupied by a crew, is one.	Little's Law (Hopp and Spearman 1996; Little and Graves 2008)
2.3. The sum of the time buffers between trade operations is zero for all locations.	Minimum cycle time; Little's Law (Hopp and Spearman 1996; Little and Graves 2008)
2.4. The number of operations has been reduced to an essential minimum.	Minimum waste (Ohno 1988)
2.5. There is no re-entrant flow.	Re-entrant flow (Brodetskaia *et al.* 2013, Kumar 1993)
2.6. There is no rework.	Minimum waste (Ohno 1988), Law of quality (Schmenner and Swink 1998)
2.7. The work flow is reliable: only work packages with mature constraints are released to operations. This also ensures that 'making-do' is prevented.	Last Planner® System (Ballard 2000), Waste of making-do (Koskela 2004)
2.8. The number of locations with work in progress is equal to the number of trade crews (i.e. WIP buffer is zero) at all times.	Minimum WIP inventory (Hopp and Spearman 1996; Ohno 1988)
3. Operations conditions (trade flow)	
3.1. Stable production rates: the variation within each trade's takt time (multiple of production rate and work quantity per location), measured as the standard deviation of the number of locations completed per unit of time, is zero.	Takt time variation (Emiliani and Seymour 2011, Schmenner and Swink 1998, Woollard and Morris 1925)
3.2. The operation time for each trade is reduced as far as possible (zero set-up and inspection times as well as minimal non-value adding time).	Single-piece flow and minimum waste (Ohno 1988, Womack and Jones 2003)

the natural unit of flow in construction is time, rather than cost or quality, and that reduction in lead time will coincide with reduced costs and improved quality.[8]

- Throughout Ballard's thesis (2000), strong emphasis is placed on the reliability of work flow. Good work flow in this context means reliable, i.e. stable and predictable flow of work packages.
- Minimization of waste (in inventory, processing, set-up time and other non-value adding work) and single-piece pull flow are aspects of the work of Ohno, (1988) and Womack and Jones, (2003).
- The Theory of Swift, Even Flow holds that the more swift and even the flow of materials through a process, the more productive that process is (Schmenner and Swink, 1998). The theory rests on the concepts of queuing theory and on the effect of bottlenecks in production flow as defined by the Theory of Constraints (Goldratt *et al.*, 2004) and on variability of the demand for product or inherent in the production operations. Among its five laws of productivity are the law of variability (the greater the random variability, either demanded of the process or inherent in the process itself or in the items processed, the less productive the process is) and the law of quality (productivity can frequently be improved as quality, i.e. conformance to specifications, as valued by customers, is improved as waste declines, either by changes in product design, or by changes in materials or processing).
- The relationships between cycle time, WIP and throughput are stablished in Little's Law (Hopp

and Spearman, 1996; Little and Graves, 2008). Cycle time is a measure of location flow. Given the specific definition of location flow and trade flow from the previous section, good work flow can therefore be said to occur when locations and subassemblies are built continuously (i.e. value is added continuously with no waiting or other waste between operations), at stable production rates, with minimized cycle times and minimal WIP.

This set (Table 2) represents an ideal set of circumstances. For real projects, evaluation must be relative, not absolute, assuming that no actual project or portfolio of projects can fulfil all of these. Good (or better) flow can be considered to be achieved when these conditions are met to some degree that is measurably greater than the degree to which they are achieved in a project considered to have worse work flow. From an implementation standpoint, this requires the ability to measure the quality of flow in construction. No such measure is currently available.

Achieving good production flow in construction

Using the portfolio, process and operations model as a starting point, it is apparent that achieving good overall construction flow implies simultaneously achieving good project flow, location flow and trade flow. Given the distribution of control over these flows across owners, general contractors and subcontracting companies, collaboration appears essential. Considering the cyclical model shown on the right-hand side of Figure 6 above, not only should GC project managers take a direct interest in achieving continuous flow for their trade crews, so should project portfolio managers consider the spread of subcontractors across their projects (and across the regional industry as a whole). This approach stands in direct contrast to the neglect of production control in traditional construction practice that is apparent from the '*Subcontracting*' sub-section above.

Likewise, managing by lowest price contract negotiation with subcontractors and suppliers (Vrijhoef and Koskela, 2000), or managing construction with a predominant cost control view, contrasts sharply with Ford's approach:

> Manufacturing is not buying low and selling high. It is the process of buying materials fairly and, with the smallest possible addition of cost, transforming those materials into a consumable product and giving it to the consumer. (Ford and Crowther, 1922, Introduction)

Ford's focus was on the flow of production, not on the negotiation of prices with suppliers. In the construction context, this is the flow of locations, and it is this area that has the greatest potential for improvement because it is the most neglected in traditional practice. The interdependence of the flows means that improving location flow can positively affect both project flow and trade flow.

There are various tools available for improving location flow, some of which naturally deal with aspects of project flow and of trade flow. Lean construction tools, such as Value Stream Mapping, Last Planner System™ (Ballard, 2000) and Andon boards are among recent innovations in construction. Tools based on Building Information Modelling (BIM), such as model checking applications, hardware and software that provide access to product information using BIM on-site, and process visualisation and management applications that integrate BIM with project status data (Sacks *et al.*, 2010), also contribute to improved location flow. Yet despite the plethora of tools, one should not lose sight of the principles. As Ford commented that the '*conveyors are only one of many means to an end',* so should lean and BIM tools be seen as some of many means to achieving good location flow.

Achieving good location flow and trade flow simultaneously is very difficult not only due to variability of the work content and the instability of the supply chains, but also due to the conflicting interests of the participants. Although productivity is a critical factor in income generation, the key objective of subcontractors is the maximisation of income per unit time and not the maximisation of productivity (Saari, 2011). This often leads to work out of sequence on-site, which then requires making-do and/or rework, accumulation of WIP, etc. In a recently observed example, a supervisor decided to allow an otherwise idle flooring crew to begin laying tiles in an area in which overhead gypsum ceilings were not yet installed. This resulted in the waste of protecting the floor tiles with boards during overhead work. When the ceiling crew arrived, the flooring work was interrupted (grouting of the joints was not yet done), resulting in re-entrant flow. In this example, the flooring crew had continuous work and greater income than would have been achieved had they had to wait. However, it came at the cost of waste and reduced productivity for all involved. Similarly, the observation that the optimal crew size for a plumbing crew was determined by the economic imperative of the crew leader to fill all the seats in the van driving an hour to the job site, rather than by consideration of the optimal crew size for maximum productivity in the work itself (Laufer and Shohet, 1991), underlines the need to consider the motivations of decision-makers within their local economic context. Decisions that may appear irrational are often the result of the narrow focus of local optimization, and their results can directly conflict with process flow optimization.

Conclusion

Manufacturing industries benefit from a wide range of research and development efforts that have resulted in sophisticated production management procedures that are rooted in theory. Unfortunately, delayed growth of a theory of production in construction, together with the prevalent perception among practitioners that the industry is fundamentally different to manufacturing, has inhibited development of appropriate procedures and tools to the level available in manufacturing.

The portfolio, process and operations (PPO) model is an attempt to summarize current understanding of production flow in construction. It proposes three levels on which construction flow can be understood: flow of projects in a regional construction economy, flow of locations within a project and flow of trade crews in and between the locations of projects. Consideration of the flow of trade crews across projects adds the relationship between the project and the operations flow, resulting in a cyclical model. This view of the flows has enabled statement of a set of ideal conditions for optimal flow.

An important limitation of the review and the model is that they do not consider the economic behaviour of the individual actors whose rationality may not always be apparent. Construction management and production control systems must consider the effects of both aspects, i.e. of production flow and human behaviour. Future development might therefore extend the PPO model to consider behavioural economics aspects. A minor limitation is that the model does not explicitly consider three additional flows that are relevant for production in construction projects. These are the flows of materials, resources (equipment and labour) and information (product/design information and process status information) that feed the operations and the process. These flows are extraneous to the three principal axes of the PPO model, and conditions for good flow should extend to them too. Ideally, they would be delivered reliably ‘just-in-time’.

The PPO model may serve as a basis for further research and development of theory and thus of better production control methods and tools. For example, it reveals the need for tools for subcontractors to manage and balance the allocation of their resources across projects. No such applications are presently available; their development and future integration with project management systems, across organisational boundaries, could provide a platform for win-win collaboration. The set of conditions for good flow provides a basis for development of quantitative measures of work flow quality that are needed to support practitioners’ efforts to improve work flow in project portfolios or in individual projects.

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Notes

1. TH = WIP/CT, where TH = throughput, WIP = work in progress and CT = cycle time.
2. In a subsequent adaptation, Schmenner and Swink positioned production systems along a diagonal between axes of variability and speed, in accordance with the Swift, Even Flow theory (Schmenner and Swink, 1998).
3. For example, some interior finishes may require that a building be enclosed and protected from weather. If exterior cladding, such as curtain walls, proceeds by façade, only achieving enclosure once the last façade is installed, the start of interior finishes may be significantly later than would be the case if an alternative exterior cladding system (installed floor by floor) were used.
4. Construction operations are also fed by subsidiary flows: materials, design information, process information (directives), equipment and money must all flow into activities, and all can experience waiting, unnecessary storage and accumulation of inventory, buffering and other forms of waste (Koskela, 2000).
5. Construction of drywall partitions or ceilings typically requires the following steps: construction of the frame by a drywall crew, installation of electrical, plumbing and other conduits by their respective trade crews, closure of the partition by the drywall crew and finally installation of finished end units (sockets, faucets, sanitary ware, etc.) by the system trades.
6. Following Koskela (2000), who introduced this term.
7. A politically correct alternative term for ‘foreman’.
8. This is not specific to construction: time is the natural unit of flow in production in general.

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