6

Supply Chain Management for Lean Project Delivery

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6.1 Introduction

6.1.1 What is a Supply Chain? What is Supply Chain Management?

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The term "supply chain" refers to a series of interdependent steps of activities or processes (sometimes sequential and sometimes overlapping) as well as flows between them, supported by infrastructure (people, equipment, buildings, software, etc.) [e.g., Simchi-Levi et al. ~~2003~~; Fine and Whitney 1996]. These flows express real or forecast customer demand

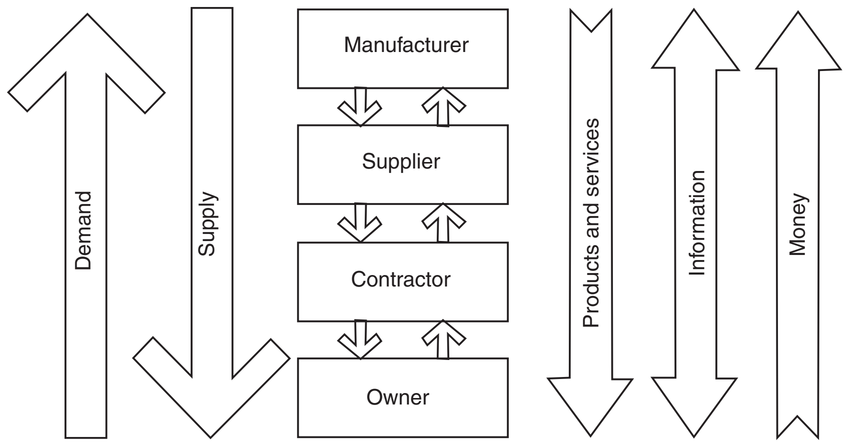

FIGURE 6.1 Example of supply and demand with flow of products/services, information, and money in a supply chain.

going in one direction, and supply going in the other direction in order to fulfill that demand. Figure 6.1 outlines the general directions of these flows. Demand and supply flow in opposite directions but may follow different routes (they are not necessarily one-on-one opposites of each other). Information flows both ways. Products and services also may flow both ways (e.g., a fabricator may ship products to a galvanizer and then incorporate returned products into larger assemblies). Accordingly, the term supply "network" might be a better characterization of this system than supply "chain" is, but the latter term is used more commonly and will thus be used throughout this chapter.

Supply chain management (SCM) refers to managing the flows of physical products and services, information, and money between the activities or process steps that companies perform, while aiming for customer service as the goal (i.e., get the right product to the right place at the right time for the right cost). Defined in this way, SCM applies to the delivery of capital projects (so-called "project supply chains") as it does to the delivery of products or services in other industries[1] (supply chains that deliver products are sometimes referred to as "product supply chains").

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6.1.2 SCM in Project Settings

A project constitutes steps to design, make, and then deliver a product or service to a customer (or customers). In order to do so, the project may acquire goods and services from a combination of preexistent and custom-made supply chains (SCs). One difference between SCM at large vs. SCM in project delivery settings is that some project supply chains are relatively short-lived: they must be established, configured rapidly,

[1] We disagree in this regard with Fernie and Thorpe (2007), who equate SCM with partnering and claim that SCM does not apply in the construction industry.

and remain flexible to match demands that vary over the course of project execution.[2] Another difference is that in project production systems, owners tend to be involved throughout project delivery and influence their project supply chains directly (they are "prosumers"[3]). In contrast, in many manufacturing production systems (especially for commodities that are made-to-stock to production targets that are set to meet forecast demand), retail customers remain anonymous until receipt of the final product (they are consumers) though they may influence supply chains indirectly. Notwithstanding such differences, SCM and new product development practices have been pushing for more individual customization (which also has been the pursuit in "mass customization" efforts, e.g., Davis 1989; Pine 1993a, 1993b; Gilmore and Pine 1997) so that several concepts and techniques used to manage various manufacturing SCs are now akin to those used to manage project SCs.

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Project supply chains may be parts of existing, longer-lived supply chains that operate regardless of whether or not any one specific project exists. Alternatively, project supply chains may be established specifically to meet one project's or several projects' needs. For example, a formwork contractor may tap into an existing supply chain to purchase lumber on an as-needed basis from a local reseller and get partial truckloads shipped from the reseller's storage location to the contractor's yard. Alternatively, while ordering from the same reseller, full truckloads may get shipped directly from the mill to the contractor's yard, bypassing the reseller's storage location. As illustrated, the supply chain from the mill to the reseller exists to meet the demands from a pool of customers, whether or not this one contractor places any order with that reseller; based on order size (to take advantage of economies of scale in transportation and handling) that supply chain flexes to suit the magnitude of the specific demand. Such flexibility is not uncommon in construction supply chains because materials and shipments are often bulky, heavy, or of exceptional size (e.g., 30 meter long precast piles), and these characteristics may weigh in considerably in SC performance metrics (e.g., economics expressed as total cost installed or total cost of ownership).

6.1.3 Narrow and Broad Views on SCM

The goals of SCM (meeting customer service/cost objectives) can be viewed and optimized from a project, enterprise, or industry perspective. Tommelein, Walsh, and Hershauer (2003) noted that "while SCM may be practiced on a single project, its greatest benefits come when it (a) is practiced across all projects in a company, (b) involves

[2] Such flexibility has been characterized as "agility" by some, but it is what we expect of "lean-ness" on projects and their supply chains (e.g., Preiss (2006) compares and contrasts agility with lean-ness). Others have used the term "leagility" to refer to the combination of lean-ness with agility [e.g., van Hoek 2001]. A key distinction to make when comparing those terms used in the literature is whether or not they apply only to making (manufacturing) or also include designing. In our view, lean includes both.

[3] "Prosuming" means involving the customer in production [e.g., van Hoek 2001, 163]. In contrast, other traditional supply chains serve consumers.

multiple companies, and (c) is applied consistently over time. In today's marketplace, companies no longer compete one-on-one; their supply chains do."

Historically speaking, SCM has evolved from materials management by broadening its scope. SCM thus includes procurement (sourcing and purchasing) and logistics (warehousing and transportation). As the scope of SCM continues to broaden, operations and production are also included, so SCM includes the design and execution of activities or process steps themselves, as well as the design and management of the system they make up, in order to deliver value to the owner. By considering more functions in an integrated fashion, SCM is increasingly better positioned to shape product and service flows so as to more optimally meet management objectives.

This broad interpretation resonates with the Construction Industry Institute (CII)'s definition [Tommelein, Walsh, and Hershauer 2003]: "SCM is the practice of a group of companies and individuals working collaboratively in a network of interrelated processes structured to best satisfy end-customer needs while rewarding all members of the chain." Other views on SCM amplify considerations different from those presented here. For example, Cox (2001) has highlighted power relationships as a means to gain leverage in SCs. While competing definitions of SCM exist, as is clear from other chapters in this book and the voluminous body of literature on this subject [e.g., Hershauer, ~~Walsh, and Tommelein~~ 2003], many authors state that delivering optimal customer service is the goal of SCM. The remainder of this chapter focuses specifically on the application of SCM in lean project delivery settings.

6.2 SCM in "Lean" Project Delivery

6.2.1 Toyota Production System

"Lean production" is a term coined by John Krafcik to characterize the Toyota Production System (TPS) [Womack, Jones, and Roos 1990]. Toyota, like other automobile manufacturers, produces cars on a large scale, but it uses a different[4] way of designing and making them [e.g., Liker 2003; Liker and Meier 2005]. The philosophy Toyota has developed and the culture it instills through company-wide use of "lean" practices has enabled it to become a world leader in automobile manufacturing. In a nutshell, this philosophy promotes "doing what the customer wants, in no time, with nothing in stores" [Womack and Jones 1996]. It focuses on value streams (recognizing how, where, and when value gets created in the process of transforming raw materials into finished goods) and shaping them to reduce waste [Rother and Shook 1999].

The lean philosophy supports Toyota's entire business enterprise, including not only manufacturing and production [e.g., Liker 2003; Liker and Meier 2005] but also new product development (a type of project production system with characteristics different from those of a manufacturing production system) [e.g., Morgan and Liker 2006], accounting, supplier relationships, strategic planning, etc. Toyota's production-systems thinking can also be applied to project settings, for example, those encountered in

[4] Many companies have been trying to copy Toyota's system, but it remains different from other production systems in many regards.

architecture-engineering-construction (AEC) project delivery. Accordingly, a theory of how to deliver projects in a lean fashion is emerging, though it is yet to be fully articulated. The term "lean construction" refers to this theoretical development.

6.2.2 Lean Construction and Lean Project Delivery

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6.2.2.1 Transformation-Flow-Value Theory as a Foundation for Lean Construction

The theory of lean construction recognizes that three schools of thought have emerged in production management and that these views are orthogonal yet complementary: one adopts the transformation view "T", the second the flow view "F", and the third the value view "V" [Koskela 1992, 2000].

Koskela et al. (2002, 213–15) characterize these views as follows:

> In the transformation view, production is conceptualized as a transformation of inputs to outputs. [The] …principles by which production is managed… suggest, for example, decomposing the total transformation hierarchically into smaller transformations, called tasks, and minimizing the cost of each task independently of the others. The conventional template of production has been based on this transformation view, as well as the doctrine of operations management. … However, this foundation of production is an idealization, and in complex production settings the associated idealization error becomes unacceptably large. The transformation view of production has two main deficiencies: first, it fails to recognize that there are phenomena in production other than transformations, and second, it fails to recognize that it is not the transformation itself that makes the output valuable, but, instead, that there is value in having the output conform to the customer's requirements. The transformation view is instrumental in discovering which tasks are needed in a production undertaking and in getting them realized, however, it is not especially helpful in figuring out how to avoid wasting resources or how to ensure that customer requirements are met in the best possible manner. Production managed in the conventional manner therefore tends to become inefficient and ineffective.
>
> The early framework of industrial engineering introduced another view on production, namely that of production as flow. … The flow view is embodied in "lean production," a term coined … to characterize Toyota's manufacturing practices. In the flow view, the basic thrust is to eliminate waste from flow processes. Thus, such principles as lead time reduction, variability reduction, and simplification are promoted. In a breakthrough book, Hopp and Spearman (2000) show that by means of queuing theory, various insights that have been used as heuristics in the framework of JIT can be mathematically proven.
>
> A third view on production was articulated in the 1930s, namely that of production as value generation. In the value generation view, the basic goal is to reach the best possible value from the point of the customer. The value generation view was initiated by Shewhart (1931). It was further refined in the framework of the quality movement but also in other circles. Principles related to rigorous requirements analysis and systematized flowdown of requirements, for example, are forwarded.

> Cook (1997) recently presented a synthesis of a production theory based on this view.
>
> Thus, there are three major views on production. … These three views do not present alternative, competing theories of production, but rather theories that are partial and complementary.

Lean construction is a TFV theory that acknowledges that all three views weigh in on production system management. In contrast, traditional construction and project management practices have amplified the transformation view, while demoting "F" and sacrificing some "V". SCM practices have amplified the flow view (as highlighted by fig. 6.1), while demoting "T" and sacrificing some "V." Lean construction applies TFV specifically to project settings such as—but not limited to—those encountered in the AEC industry. Lean SCM, an integral part of lean construction, thus differs from SCM at large in that it aims to balance all three.

Lean construction adopts a holistic and systemic view of project delivery, recognizing that the project delivery system may be viewed at different levels with TFV pervasive in all, namely (a) the physics of the task (how work at the lowest level actually gets done), (b) production (how work relates to other work), (c) organizations (how people and the relationships between them affect how work gets done), and (d) formal and informal contracts (how incentives motivate people to behave or production to be organized in one way or another).

At the production level this system includes five phases (fig. 6.2): (a) project definition, (b) lean design, (c) lean supply, (d) lean assembly, and (e) use. Spanning these phases are production control and work structuring. Production system design, operation, and improvement are driven by work structuring and production control.

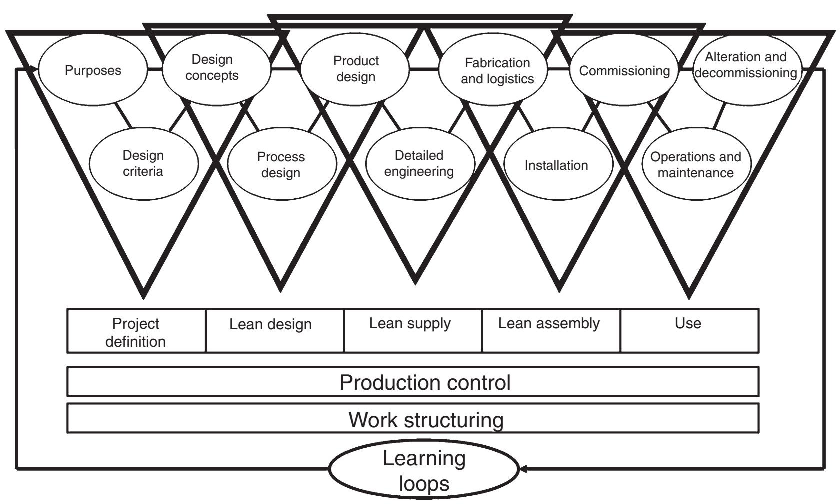

FIGURE 6.2 Lean Project Delivery System™ (LPDS). (From Ballard, G. Lean Project Delivery System™. White Paper-8 (Rev. 1). Lean Construction Institute, Ketchum, ID, 23 September, 2000a. With permission.)

6.2.2.2 Work Structuring

Lean work structuring is project production system design (process design integrated with product design to deliver a project) and extends in scope from an entire production system down to the operations performed on materials and information within that system [after Ballard et al. 2002]. Work structuring means "developing a project's process design while trying to align engineering design, supply chain, resource allocation, and assembly efforts" [Howell and Ballard 1999].

"The goal of work structuring is to make work-flow more reliable and quick, while delivering value to the customer" [Howell and Ballard 1999]. In particular, work structuring views a project as consisting of production units and work chunks [Ballard 1999]. A production unit is an individual or group performing production tasks. Production units are recipients of work assignments. A work chunk is an output of a production task that is handed off from one production unit to the next. In the process of performing a production task, each production unit may or may not make changes to the boundaries of the work chunk before handing it off to the next production unit. While performing tasks, production units typically will add value to work chunks. In turn, these chunks morph while moving through the production system until they become a completed product.

Work structuring involves determining: (a) in what chunks will work be assigned to production units, (b) how chunks will be sequenced, (c) how chunks will be released from one production unit to the next, (d) where decoupling buffers will be needed and how they should be sized [Howell, Laufer, and Ballard 1993], (e) when different chunks will be done, and (f) whether consecutive production units will execute work in a continuous flow process or whether work will be decoupled [Tsao, Tommelein, and Howell 2000; Tsao 2005]. These determinations are fundamental to production system design, be it project production systems or SCs. Nevertheless, these determinations are not explicitly and routinely made in practice today. In contrast, current work structuring practices—if it is appropriate to call them that—mostly focus on local performance and are driven by contracts, the history of trades, and the traditions of craft. Hampered by these drivers, decision makers rarely take the liberty to consider how to optimize the entire production process. The resulting work breakdown structures more-often-than-not prevent the smooth flow of work and hamper performance effectiveness. In contrast, work structuring, as defined here, adds a production system's view to the other views, while aiming to reveal such and other optimization opportunities through adoption of a holistic view on project delivery, ranging from project definition through use of a capital facility (fig. 6.2).

6.2.2.3 Production Control

Production control (as also discussed in chapter 2 of this book) means shaping work and planning it at successive levels of detail, covering with greater accuracy increasingly shorter time periods into the future as time for action approaches, while making adjustments as needed to steer the project towards best meeting system objectives during project execution. Its objective is to maximize the likelihood of getting the work done according to project objectives. Plan reliability—a key objective in lean project delivery—can be managed by means of the Last Planner™ system [Ballard 2000b]. This system embraces a methodology to shield planned work from upstream variability, thereby allowing performance improvement to take place behind the shield [Ballard and Howell 1998] and work flow to be stabilized upstream from the shield[5] [Ballard and Howell 1994].

6.3 Project Supply Chains

Projects are undertaken to create a unique product, service, or result [PMI 2004, 5]. They can be conceptualized as temporary production systems. This means that, in contrast to ongoing business operations, which take place in a manufacturing or service facility, a project has a start time and an end time. A project would not be designated as such if it went on forever. A project production system of course does not exist in a vacuum: it is established in context and draws upon existing supply chains (that support permanent production systems) to "feed" its needs.

Figure 6.3 shows a work-structure model, highlighting primary flows that must be managed in a construction project. The "Con" (construction) processes flow to an intersection, an assembly point <Con C, 1> (where processes merge and products get matched[6]), of which there are obviously very many in a project. For each construction installation such as <Con A, 1>, there is a prior act of engineering/design such as <Eng A, 1> and procurement (purchasing, fabrication) such as <Proc A, 1>. The arrows connecting the <Eng X, i> boxes indicate that they must be coherent with one another,

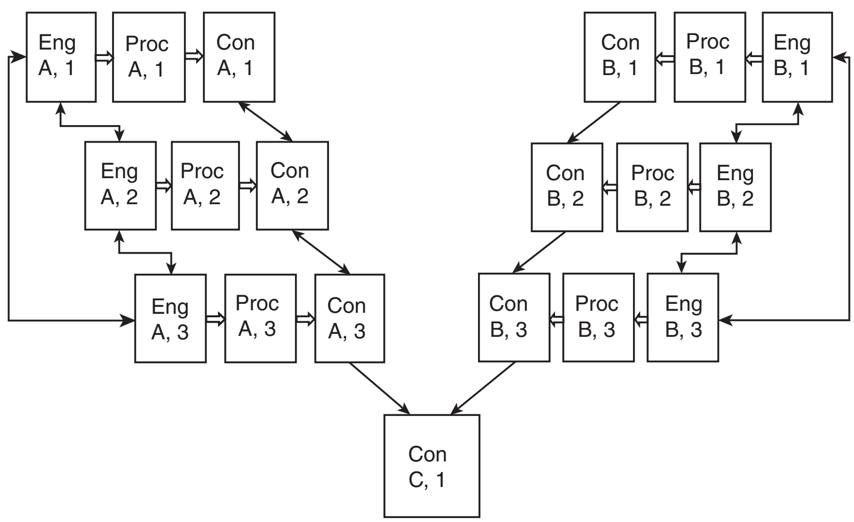

FIGURE 6.3 Work structure model of a project production system.

[5] More details about the Last Planner™ system are presented in chapter 3.

[6] Tommelein (1998) presents a computer model to illustrate how uncertainty involving matching problems may be accounted for in project planning and execution.

amounting ultimately to a description of a system—structural, mechanical, electrical, etc. The model could be expanded to show product supply chains and the corresponding flows that support fabrication and site deliveries as well.

Figure 6.4 expands the view on the project work-structure model in that it also includes product supply chains. The wide arrow shows project delivery as a progression through time from start to completion, through the phases of lean project delivery (as detailed in fig. 6.1). This arrow is akin to a so-called "development chain" in SCM [Simchi-Levi, Kaminsky, and Simchi-Levi 2007], involving project participants such as the owner, designers, contractors, and other providers of specialist services who contribute to a new product's development.

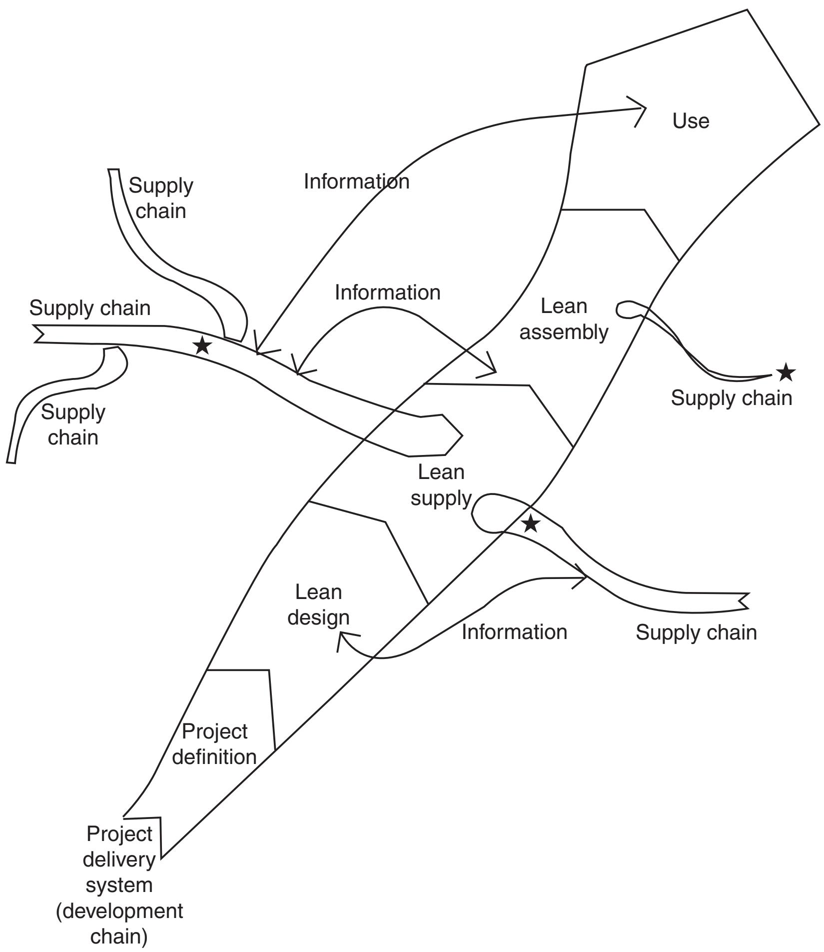

FIGURE 6.4 Project supply chain hinging on preexistent and custom-made supply chains.
Note: Stars denote customer order decoupling points (CODPs).

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In a narrow and traditional sense, supply refers to a supplier handing-off a "black box" product to a project participant. "Black box" means that the supplier designs and makes the product while treating the project participant as a consumer. The delineation appears to be defined by the customer or product on one end, and by the choice where to "black box" supply on the other, i.e., to aspire to only transactional relationships. Accordingly, suppliers are not traditionally thought to be project participants.[7]

In contrast, lean project delivery includes suppliers in the team, recognizing that they may offer not only "black box"[8] products but could also deploy their production system to suit the project. Indeed, a project is a set of resources structured to achieve the project's objectives, and hinges on preestablished production systems from which goods and services are acquired. The project hinges on supply chains in the Lean Supply triad (fig. 6.2). A variable is the extent to which those preestablished production systems are objects of coordination and shared fortune for the contractor or owner, as opposed to existing entirely independently of the contractor or owner. Consequently, project SCM could be understood as the design, execution, and improvement of SCs independent of any one project, and the design, execution, and improvement of the project supply chain.

Figure 6.4 shows several narrow arrows, each exemplifying a supply chain that "feeds" the project. There typically will be many more of these project-feeding supply chains, but only a few are shown. In the course of work structuring, these supply chains were selected from among many that exist independently of whether or not a particular project materializes (i.e., the project exists in a "universe" of supply chains). Some supply chains may be used "as-is," to hand-off a product to the project. Others may have their production system tailored to meet a specific project's requirements. Custom-tailoring is shown in figure 6.4 by the stars that indicate where in the supply chain the product or service becomes customer-specific (this star marks the "customer order decoupling point," a concept that will be further detailed later). The double-headed arrows illustrate how information may flow in the system, from suppliers to project participants in different phases of project delivery, and vice versa. It is through integration of such various supply chains that project supply chain objectives are pursued.

6.4 Selected Lean Production System Design Concepts and Principles

We next define concepts and principles to be used when designing lean (project) production systems. These consider work structuring to go hand-in-hand with production control and establishment of feedback loops to promote learning. Production system design is said to be "lean" when it is done in pursuit of TFV goals [Ballard et al. 2002].

[7] To illustrate this point, note that in the first decade or so of functioning of the CII at UT Austin in Texas, CII membership included only owners and contractors. Only in more recent years have suppliers been invited to the table.

[8] Toyota has developed different SCM practices based on the degree to which its systems can be decomposed, and accordingly refers to "white box," "gray box," and "black box" items being procured from suppliers [e.g., Fujimoto 1994; Ward et al. 1995].

6.4.1 Customer Order Decoupling Points and Push-pull Boundaries in Supply Chains

In the process of work structuring, the process steps and wait times a product is subjected to while being transformed from raw materials into a final product can be mapped out. This map may take the form of a "value stream" or a "cross-functional diagram," which shows tasks and hand-offs across organizational boundaries. In any case, along the supply timeline it depicts, the customer order decoupling point (CODP) marks the point where a product is customized to meet a specific customer's needs (shown by means of a star in fig. ~~6.3 and~~ 6.5).

AU: There is no star visible in fig. 6.3. Please clarify.

Based on this CODP concept, Wortmann, Muntslag, and Timmermans (1997) developed a typology of manufacturing and supply approaches differentiating products that can be made-to-stock from those that have to be made-to-order (fig. 6.5). To the left of this point, upstream to "Raw materials," production is driven based on forecast demand. To the right of this point, downstream all the way to "Product delivered to customer," production is driven based on actual demand. The CODP defines the "push-pull boundary" because forecasting means pushing products through the supply process without knowing exactly who the customer will be, whereas sales reflect the pull of a specific customer. Because forecasts are speculative—they are always wrong (due to their stochastic nature) and even more so when projecting further out into the future—lean production systems are designed to produce products and deliver services based on customer pull where possible.

Products that remain undifferentiated until they are sold "off the shelf" are said to be "made to stock" (MTS). MTS products can be produced based on either forecast need or a specific customer order, but it is often the former, as they are mass produced to reap the benefits of economies of scale. For example, SCs for lumber, drywall, bathroom plumbing, and many light fixtures are like this (e.g., a fixture sold in a retail store is custom-wired during installation).

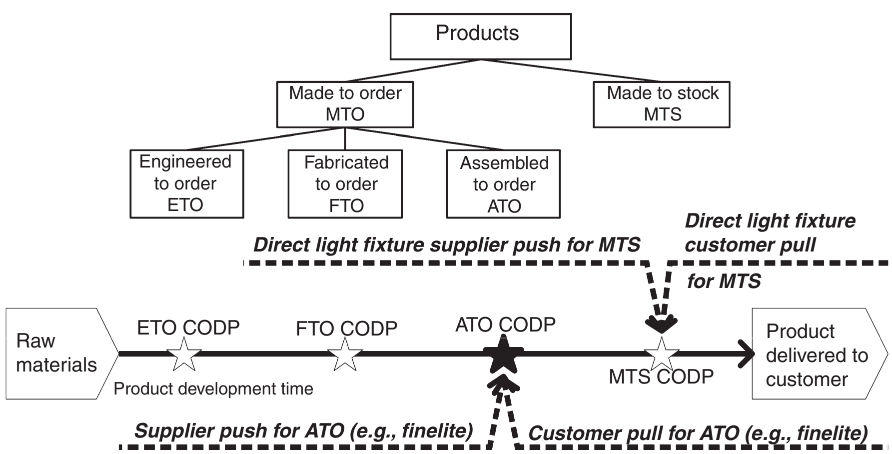

FIGURE 6.5 Typology of product supply approaches recognizing customer order decoupling points. (After Wortmann, J. C., Muntslag, D. R., and Timmermans, P. J. M. (eds). *Customer-driven Manufacturing.* Chapman & Hall, 1997. With permission.)

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Alternatively, products may be "assembled to order" (ATO) by putting together off-the-shelf parts to suit a customer's desired configuration prior to delivery to the customer. Configuration and assembly is done at a location either on- or off-site, but not at the location of final installation. As a result, ATO production systems incur a lead-time penalty (i.e., assembly is done some time before final installation). Lean producers strive to continuously reduce such lead times so that other performance metrics may offset the costs of ATO production, e.g., the lead-time penalty may be outweighed by a reduction in installation time or an increase in safety, handling efficiency, or quality. For example, SCs for light fixtures may be structured for ATO production [e.g., Tsao and Tommelein 2001].

Furthermore, products may be "fabricated to order" (FTO) (e.g., by taking off-the-shelf parts and cutting, drilling, or welding them) or "engineered to order" (ETO) (e.g., using engineering design and analysis to determine which components are needed and how to configure them). For example, SCs for pipe supports may be structured for FTO or for ETO production [Tommelein, Walsh, and Hershauer 2003; Arbulu et al. 2002, 2003]. Figure 6.5 illustrates the corresponding CODPs and shows increasing lead-time penalties for ATO, FTO, and ETO products.

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While figure 6.5 marks the CODP as a single point (star) on the timeline, "the concept does not only center around deciding at what level in the chain postponement is to be applied, it is also a matter to what degree is it applied" [van Hoek 2000]. So, work structuring is employed to decide which suppliers to work with, which products or services to get from whom and when, and where to position the CODP. From a TFV perspective, the location of the CODP affects where customer requirements (information flows) need to be injected in the supply time line and what lead time will be required downstream from that CODP to the point of customer hand-off. It thus affects the extent to which a supplier can deliver value both in terms of product specificity as well as responsiveness in meeting varying project demands.

6.4.2 Lean Principle of Continuous Flow

Note that CODPs exist whether or not a supply system is lean. Lean production systems are designed to use customer pull where possible to set the rhythm for production. Producing products at the so-determined customer-demand rate, lean systems also strive to achieve "continuous flow," i.e., get raw materials to proceed through all production steps without undue inventory or other waste. The lean production literature describes these concepts in detail [e.g., Rother and Shook 1999; Rother and Harris 2001; Harris, Harris, and Wilson 2003; Smalley 2004; Womack and Jones 2002]. In a nutshell, continuous flow may be achieved through batch sizing (ideally, batches of one to achieve one-piece flow) and synchronization of production steps, combined with pull. Example applications of pull used in construction SCM are *kanban* systems for delivery of ready-mix concrete [e.g., Tommelein and Li 1999] and precast panels [e.g., Arbulu et al. 2003], and constrained work in progress for rebar cages [e.g., Arbulu 2006].

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Where pull is not feasible, production system steps may be decoupled using buffers. The use of buffers is necessary in systems subject to uncertainty or variability, as these are particularly detrimental to performance [Hopp and Spearman 2000].

Correspondingly, the lean approach to production system design is to first root out all unwanted variability,[9] and then accommodate the remaining variability in its design.

6.4.3 Positioning and Sizing of Buffers

AU: Is this correct? Would 'be necessary' or 'exist' be better?

Buffers are holding places for products, resources (people or equipment), or information, or time delays in between steps in a production system. If continuous flow were always possible, buffers would not be needed. Until that lean ideal has been achieved, buffers ~~will occur~~ and their locations and sizes must be judiciously determined in the course of production system design. Buffers can be used to serve a variety of functions.

6.4.3.1 Use of Inventory Buffers in Project Production Systems

Inventory buffers comprise raw materials, work in progress, or finished goods. Based on Schmenner's work (1993), the major functions of raw materials inventory can be characterized as:

- To protect (buffer) against the unreliable delivery of needed raw materials.
- To hold costs down if possible by buying in large quantities or by buying at propitious times.

The same author characterized the major functions of **work-in-progress inventory** as:

- To permit one segment of the process to operate under a different production plan and at a different rhythm from another segment of the process (e.g. Howell, Laufer, and Ballard (1993) called this "decoupling inventory").
- To permit individual work stations or machine centers to produce parts, assemblies, or materials in sizable batches, rather than individually (the lean, ideal "one-piece-flow") or in smaller batches. Such "cycle inventory" acts to tide the process over until the next setup.
- To protect (as a buffer) against the unreliable (a) delivery of materials from elsewhere in the production process, (b) completion of prerequisite work, or (c) release of information.

He also characterized the major functions of **finished goods inventory** as:

- To supply the product quickly to the consumer. Made-to-stock products have zero lead time.
- To protect (as a buffer) against the uncertainties of customer demand. Buffers are thus a substitute for information, that is, if one had perfect information about future downstream customer demand (and likewise, of upstream supply), one could reduce buffer sizes.

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[9] Hopp and Spearman (2000) distinguish two types of variability: (a) bad variability is the result of unplanned outages, quality problems, accidental shortages, or human skill; and (b) good variability may stem from the purposeful introduction of differences in product or process characteristics as a means to increase the system's ability to match or create market demand (customer value). Bad variability is always unwanted.

- To smooth (through the accumulation of finished goods inventory) demand on the process even while demand is erratic or temporarily depressed (balance capacity against demand).
- To lower costs for shipping and handling (optimize the batch process).

In addition to inventory buffers, the systems' view on project production also includes so-called "capacity buffers," "time buffers," and "plan buffers" among the variables in the design, execution, and improvement of the project-cum-supply chain.

6.4.3.2 Use of Capacity Buffers in Project Production Systems

A capacity buffer is a resource that intentionally is not fully utilized. In a system subject to uncertainty, lean practice is to schedule resources (e.g., people and equipment) at less than 100% utilization because the manifestation of that uncertainty might jeopardize system performance (e.g., if work is planned to make full use of a resource, that work will not get completed in the anticipated time period if a glitch occurs). There is value in having resources on standby—the result of such underloading—to deal with the unexpected, as it yields greater plan reliability (nevertheless, providing excess capacity is contrary to the project management wisdom that says resources must be kept busy all the time). Lean production recognizes that reliable flow is more important for increasing throughput (customer value) than high resource utilization is, and therefore relies on capacity buffers. Most production systems are not balanced anyway, so high utilization cannot be obtained for all resources in each and every step.

6.4.3.3 Use of Time Buffers and Merge Bias in Project Production Systems

A time buffer is a delay or a lag added at the end of a sequence of steps that has an uncertain finish time, in order to guarantee the start time of the immediately succeeding step.

Time buffers may be particularly useful in production system design when SCs merge, thereby creating a network. Merge bias occurs when several inputs must all be present in order to start a process step or task, that is, a shortage of any one of them will prevent the start of their successor. When the arrival of one (or several) of these inputs has some degree of variability, the likelihood of successor delay increases. Furthermore, when the number of inputs increases, each one arriving independently of the other, the likelihood of successor delay multiplies; this system characteristic is known as the merge bias. Merge bias affects the time it will take for a product to flow through the system.

Koskela (2004) noted that in construction, many tasks get started even when some inputs are in short supply, on the presumption that the supply of those inputs will catch up with the production need for it. Of course, there is no guarantee that this will happen, unless the supply system is designed and controlled to make it happen. He called this the "make-do" mind-set and characterized it as a type of waste, because all too often supply is unable to deliver and as a result steps fall short of being completed as planned. When pressured to make progress, workers use what is readily available and thereby forego the best-laid plans. They end up working in potentially unsafe conditions, produce faulty work, and make early progress, but at the expense of their own follow-on work[10] or that of others, and fail to meet the customer's needs. Thus, if the supply system is not managed well, completion of such steps becomes uncertain, thereby injecting unreliability into the work flow, which in turn hampers performance.

6.4.3.4 Use of Plan Buffers in Project Production Systems

A plan buffer is a step or task that is part of a plan but that is (1) not yet scheduled or (2) scheduled but can be rescheduled. Flexibility exists in reordering those steps or tasks (i.e., work flow). Plan buffers are hidden when hierarchical plans are created because the master plan (master schedule) typically defines tasks at an abstract level. Those tasks are broken into smaller ones when look-ahead plans and weekly work plans are created. In the process of breaking down tasks, decisions must be made regarding their definition and sequencing while adhering to the original plan. Thus, smaller tasks make up a buffer from which selection needs to be made in order to yield a good, overall system performance.

6.4.4 Lean Principles of Muri, Mura, Muda

We next summarize three objectives Toyota pursues at the same time, because they apply to project production system design as well as to SCM. They are (a) to appropriately use resources, (b) to balance loads, and (c) to eliminate waste (captured respectively by the Japanese words "muri," "mura," and "muda") [Kitano 1997; Liker 2003].

Muda refers to the elimination of waste, which Ohno (1988) classified using seven types: (a) defects in products, (b) overproduction of goods not needed, (c) inventories of goods awaiting further processing or consumption, (d) unnecessary processing, (e) unnecessary movement of people, (f) unnecessary transport of goods, and (g) waiting by employees for process equipment to finish its work or for an upstream activity to be completed. Womack and Jones (1996) added "design of goods and services that fail to meet user's needs" and Koskela (2004) furthermore added "make-do" as another type of waste.

Mura refers to load balancing. Mura is reflected in just-in-time system concepts (supplying the production process with the right part, at the right time, in the right amount, using small buffers, using pull [Kitano 1997]). In the context of SCM this includes striving for level production (supply) (e.g., through use of one-piece flow, lead-time reduction in order to be able to react to changing project needs, and modularization) as well as demand (e.g., using the Last Planner™ system).

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Muri refers to using resources appropriately. It may be achieved, for example, using standardized work, setting a reasonable customer-demand rate to drive production, and defining a logical flow of work [Kitano 1997].

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6.5 Lean Supply

With these concepts and objectives for project production system design and SCM in mind, we now return to the Lean Project Delivery System™ (LPDS) (fig. 6.2) and focus

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[10] It is well known that the last x% of work on an activity tends to take disproportionately more time than remains on the schedule to complete that activity.

on lean supply. Lean supply in the LPDS includes "product design," "detailed engineering," and "fabrication & logistics." Through product design, lean supply connects to lean design. Through fabrication and logistics, it connects to lean assembly. As mentioned, the Lean Supply triad is the hinge between the project production system and SCs. Viewed from this perspective we describe various SCM tools and techniques, and state how they contribute to improvements with regards to TFV.

6.5.1 Product Design for Lean Supply

Cross-functional teams: "Lean" thinking strongly advocates the inclusion of suppliers in design, so suppliers will be part of the lean project delivery team. Lean design pursues "design for X" (DFX), where X stands for criteria to assess TFV (such as source-ability, constructability, maintainability, sustainability) including SC performance. For example, suppliers may advise designers on standard and easy-to-install/maintain products, or on their process capability, or transportation and storage means, in order to curtail product and process variability. Suppliers, fabricators, procurement specialists, logistics services providers, and production units can inform a design team about the realities of execution possibilities, requirements, and constraints, thereby helping the team to generate value and eliminate waste in the process of making more informed decisions, especially when considering SC strategies. A challenge is to bring suppliers in early enough so they can fully contribute to the team, while rewarding them for their engagement even if no product sale is guaranteed.

Supplier alliances:[11] Supplier involvement in a project does not need to be initiated when that project starts and end when that project is completed. A supplier alliance is a long-term relationship between a buyer (e.g., owner) and a seller (e.g., supplier) that spans multiple projects and thus results in a more permanent supply chain to meet a customer's needs. It tends to focus on specific product families (e.g., precast concrete elements or engineered-steel buildings) or services (e.g., software support). Due to its multiproject nature, alliances can address opportunities and needs at the enterprise level. On occasion, suppliers may get even more deeply entrenched with owners and support the development of their business case.

An alliance is a substitute for the many one-on-one transactions that otherwise are developed when specific project needs arise. Advantages of alliances are efficiencies stemming from longer-term relationships including collaboration on joint product and process development (value creation through such means as standardization, target costing, risk pooling, demand leveling, and increasing demand predictability further in the future) and the incentives it brings for alliance participants to invest in developing such efficiencies. Disadvantages are the trust and investment needed to develop them, and potential loss of market competition.

[11] In some contexts, "alliance" refers to a particular contractual arrangement. In contrast, here we simply use this term to denote a longer-term agreement between a buyer and a seller.

6.5.2 Detailed Engineering for Lean Supply

A question of work structuring in supply chains is "Which party will detail the design?" While detailing may be thought of as the last step of completion of design, instead we view it as the start of construction [Tommelein and Ballard 1997]. Fabricators and installers engaged in detailed engineering for lean supply can add significant value to the production system, because they are familiar with intricacies and alternative means for doing the work and the execution environment (e.g., transportation, handling, trade interference, skill availability).

Lead time reduction: When products have long lead times (e.g., ETO and FTO products in fig. 6.5), it is hard to achieve one-piece flow and use pull mechanisms. This is particularly true when submittals and approvals are required in addition to custom-making, and uncertainty can manifest itself at many occasions. Accordingly, fabricators and installers are well positioned to reduce product cycle times and improve throughput. They can strive to reduce batch sizes and eliminate multitasking practices. Through their early involvement in design they can also alleviate—if not eliminate—the design-bid-*redesign* cycle. These practices help to achieve flow (F) in the production system.

Shorter lead times also enable designers to keep their options open longer. Use of a technique called "postponement" affords designers more time to explore alternative solutions with other project participants, suppliers, and stakeholders. This practice reduces waste in the project because it avoids rework (e.g., a solution that gets selected early on based on one view, may prove to be infeasible based on other views or when additional information becomes available over time) and generates value to the project because the assessment of alternatives can be gauged by combining values ascribed from various views.

Standardization: Suppliers may also recommend that the team use standard products and processes (or develop them if no existing ones are satisfactory) (muri), rather than custom-design everything from scratch. Standardization reduces the workload pertaining to submittals and approvals. Furthermore, use of multiples of the same product helps to alleviate matching problems [Tommelein 1998, 2006], simplifies all handling, eases installation, allows for risk pooling, and promotes learning. Lean practitioners develop standard products and processes in order to be able to gauge deviation from those standards. This helps not only to control production, but also to experiment with new ways of doing things (e.g., kaizen), which in turn leads them to develop better standards.

Information transparency: A lean practice is to make system status information available to those who need it, so that there is no need for guesswork or speculation (waste) to know actual demand or system status. System-wide transparency in SCs helps to avoid the Bullwhip Effect that results from people otherwise speculating what customer demand might be, one or several steps removed from them in the SC, and thereby injecting variability into the system [Forrester 1961; Lee, Padmanabhan, and Whang 1997].

6.5.3 Fabrication and Logistics for Lean Supply

Provide materials, tools, and information to workers at point of use: Several products may be combined into a single handling (packaging) unit (the process is sometimes referred to as "kitting" or "bagging and tagging"). Parts can be similar or dissimilar but all parts in the unit will be used together, e.g., installed in each other's vicinity or handled by a single person or crew. The advantage of providing materials, tools, and information to workers at point of use is that workers will not need to spend extra time to locate and count the needed parts (mura). Kitting can be done away from congested work areas, at a location where it can be managed better and less expensively. This practice consists of creating a CODP and moving it upstream in the SC. Pushing the "matching problem" upstream in this way will be successful only when the final demand for the parts in the kit and the timing of need for the contents of the kit are well known. In conditions of uncertainty, the value of kitting is diminished and it can even be counterproductive.

Control of transportation means: Many construction products are shipped by the supplier (seller) who often takes responsibility for the load while it is in transit, but as a result may use large batch sizes (full truckloads) and impose long lead times. The buyer may offer incentives to the supplier to make supply reliable and responsive to the project needs, e.g., to get just-in-time deliveries. Alternatively, the contractor (buyer) can take on this responsibility, thereby gaining control over the supply.

Load consolidation: Goods shipped by suppliers to one project may be combined with goods for other projects in order to save on shipping costs—an opportunity for suppliers to apply inter/intraproject SCM. This can create a win-win situation; for example, some commodity suppliers offer supplier-managed-inventory services with daily replenishment in regions where they have multiple customers.

An unfortunate consequence of loading trucks to capacity is that extra time may be needed to achieve this load, thereby delaying the timing of the shipment. This time-cost tradeoff must be considered when one is aiming for reducing cycle time in the supply chain.

Conversely, a project could send out a vehicle to pick up loads at different supplier locations, or large companies with ongoing work in a region could pick up loads for multiple projects from one or multiple suppliers.

Third-party logistics providers: Third-party logistics providers are more common in the manufacturing industry than they are in construction. They arrange not only for transportation of goods, but also package goods as needed for easy distribution, thereby saving time later on for locating and retrieving goods. For example, some drywall suppliers also stage pallets with drywall during off-hours in each room as specified by installation crews.

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Logistics centers: Logistics centers are places for handling one or more operations pertaining to the delivery of products or services to projects. These centers generally are not places where goods are produced [Baudin 2004], but some fabrication may take place there. Logistics centers can be configured to provide a wide range of functions such as: receiving, storage, break-bulk, sorting, assembly, cargo consolidation, transport, distribution (direct shipment, shipment with milk runs, etc.), distribution network management including vehicle routing, package tracking, and delivery, e-commerce services, etc. These functions can be catered to suit the requirements of one or several SCs [after Hamzeh et al. 2007], summing the demand for certain products and thereby offering the benefit of risk pooling.

6.6 Conclusions

This chapter presented a production-systems view on SCM and the corresponding principles for lean production system design that consider transformation, flow, and value when delivering customer service. According to this view, a project becomes a part of a supply chain by design, acquiring goods and services from a combination of preexistent and custom-made supply chains, each providing goods and services to the project customer, who in turn may use the facilities provided to produce goods and services for others, ad infinitum. SCM therefore is an integral and important part of lean product delivery. It concerns not only the "lean supply" triad in LPDS™ but more broadly supports "work structuring" (design) of the overall production system. Lean project SCM includes selecting and shaping existing SCs, or constituting new SCs as needed to meet production system requirements of one or several projects. It encourages suppliers to not only transact products but also to consider tailoring their production system to suit a project's needs and set up relational agreements in order to enhance performance and maximize value in the delivery of the specific project(s) at hand.

Contractual relationships can offer incentives or disincentives for SC participants to view the project holistically and strive to meet TFV objectives; they can drive or stifle work structuring efforts. A failure to understand the entire SC results in local decision making that is often contrary to the optimal function of the entire chain.

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