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Lean engineering logistics: load leveling of design jobs with capacity considerations

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Abstract. Achieving productivity improvement in engineering organizations involved in product development can be a daunting and complex task, commensurate with the complexity of the products being designed. The goal of this paper is to expand on the notions involved in the lean engineering body of knowledge as currently implemented in a major aerospace firm. Relying on key notions developed in a novel lean engineering financial performance model, the authors integrate lean manufacturing theories, inventory management, production planning and scheduling, improved value stream mapping, project portfolio management, and linear optimization to offer a coherent global logistics approach supporting lean promises of a more efficient engineering organization with reduced lead time and waste and improved customer and shareholder value.

Résumé. L'amélioration de la productivité peut s'avérer une tâche redoutable et complexe, à la mesure de la complexité des produits en développement, pour les entreprises d'ingénierie engagées dans le développement de produits. L'objectif de cet article est d'élaborer sur les principes actuels mis de l'avant dans le domaine des connaissances relatives à l'ingénierie allégée telle que pratiquée dans une importante firme de l'aérospatial. Basé sur les notions-clés développées dans le contexte d'un modèle novateur de performance financière d'ingénierie allégée, les auteurs intègrent les théories de la production allégée, la gestion des inventaires, la planification et l'ordonnancement de la production, la cartographie améliorée de la chaîne de valeur, la gestion du portefeuille de projets et l'optimisation linéaire pour offrir une approche logistique globale cohérente en soutien aux promesses de la théorie allégée visant à assurer une organisation plus efficace des procédés d'ingénierie avec une réduction du temps d'exécution et du gaspillage, et une amélioration de la valeur client ainsi que de la valeur pour les actionnaires.
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Introduction

Achieving new product development (NPD) objectives on budget is still a dream for some organizations, as pointed out by Bashir and Thomson (2004). Meeting budgets is becoming increasingly important in civil aerospace, given the intensifying competitive pressure firms face and shareholders expectations for return. Current profitability and net cash flow of aerospace engine manufacturers may be affected in the short term by the uncertain research and development expense inherent in these complex development programs, and future cash flow and profitability depend on an uncertain initial sales volume estimate. Fortunately, academics, industries, and governments have joined efforts in the last few years and produced an abundant set of ideas, tools, and approaches to help provide the much needed improvements in this exciting field, such as those from the Massachusetts Institute of Technology Lean Aerospace Institute (LAI) (http://lean.mit.edu/). This paper briefly introduces the concept of lean engineering in the field of NPD as a methodology that achieves the goals of "better, faster cheaper" (McManus et al., 2005). We briefly review the main dimensions of lean engineering in three key areas, namely, creating the right product with efficient engineering processes and with effective life cycle and enterprise integration.

Taylor (2005) pointed out one of the weaknesses of lean techniques as being the "lack of a clear and workable financial model to measure cost of current operations and potential financial benefit of lean improvements across the value chain." We thus briefly review a novel lean engineering financial model that has been developed and has been used for 2 years now to measure progress and justify further work on lean in a major aerospace engineering firm. We focus on some of the most important attributes that can help to improve the productivity of the engineering NPD system and related processes.

From experience, the difficulty in introducing changes to complex engineering and design systems such as those discussed earlier resides less with the understanding and integration of the concepts themselves, but rather with their acceptance and use in an optimal manner. We thus explore some of the factors that can help support the successful implementation of those changes through a discussion of a current implementation.

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Drawing from observations from the aforementioned implementation from the actual design system efficiency measurements in an aerospace company, and from the work by Braglia et al. (2006) on critical path value stream mapping, we postulate that the next level of improvement in the system can be achieved by better coordination of jobs and required resources in this complex design value stream.

More specifically, we discuss the current proposal for the establishment of a high-level engineering demand management, load leveling, and engineering job scheduling practice in a major aerospace firm in Canada, building on equivalent concepts from their manufacturing counterparts (Silver et al., 1998). Updated plans from various projects are aggregated at the enterprise level, and various algorithms and heuristics are presented and evaluated against key performance dimensions.

Lastly, using the theory of constraints by Goldratt and Cox (2004), we focus on a bottleneck of the engineering process and show how key controllable factors can support business objectives of managing a portfolio of jobs at minimum cost with maximum throughput. Linear programming and optimization techniques applied in the field of job scheduling can effectively support the managerial decision making involved in the logistical allocation of resources in a matrix-based multiproject environment together with appropriate lean visual communication techniques.

Overall, a new framework for implementing lean engineering is presented, and the implications for practical application are explained. Improved engineering logistics is enabled by adequate planning and estimating ability. Our proposed approach should also result in better execution; a pilot project should be established to confirm this postulate. According to Bashir and Thomson (2004), only 26% of projects in the United States are completed on time and within budget. Improved engineering logistics should reduce the level of surprises, helping to ensure that the expected economic return of the project is in line with the original business objective.

Previous work on lean engineering logistics

Logistics is commonly understood to be the "the time related positioning of resources" (http://en.wikipedia.org/wiki/Logistics). One key related theme within lean is achieving flow; in the lean engineering context this means ensuring that the positioning of engineering resources is appropriate to support the flow of intellectual work in progress. Oppenheim (2004) discussed the application of lean product development flow (LPDF) and suggested using weekly deliverables and review meetings to achieve flow. He suggests that the best area to apply LPDF is in complex legacy-based systems or simpler systems, since these would typically involve mature technologies and exhibit time stability. On the other hand, complex large integrated open systems (CLIOS) or complex frontier systems ("very large and complex systems either exceeding the boundaries of traditional system engineering, or complex multi-year space or defence systems seen in space and defence") would exhibit a high level of uncertainty and time delay associated with fundamental research and are thus not likely candidates for lean engineering.

Oppenheim (2004) proposed using a value stream mapping (Rother et al., 2003) (VSM) approach at the project level to identify key project deliverables in time and to identify the waste that can be eliminated from product development projects. He suggests that the reduction of throughput time (i.e., product development lead time) is one key benefit resulting from the application of LPDF. His main ideas are the application of VSM techniques in the definition of the project deliverables, the establishment of a weekly takt time period, and frequent integrative events for the project. He advocated the use of a varying workload over time to meet weekly deliverables and schedule estimates.

MacKenzie (2006) confirmed the applicability and usefulness of VSM principles in a program office type of organization.

The approach to scheduling advocated by lean proponents is one where, rather that providing multiple discrete schedules for every work centre that quickly become obsolete once a change occurs in plans, the only schedule provided is for the pacemaking work process (McManus, 2005) with the other work centres linked to it in various ways (first-in first-out (FIFO) lanes, supermarkets and pull systems, etc.).

Chan et al. (2006) have proposed a model to optimize the scheduling of employees with multiple skills using mixed integer programming. Their proposed approach integrates capacity planning over a given horizon with a scheduling model that details the assignment of employees to activities or skills. They discuss the usefulness of employee proficiency level by skill. Bashir and Thomson (2004), on the other hand, identify a difficulty to expertise factor to be used in adjusting the effort prediction for an engineering job.

In the next section we provide some basic explanations of the lean approach and elaborate further on the lean engineering model and key metrics of the lean engineering business model.

Lean approach

As discussed by Womack and Jones (2003), lean is a systematic approach that essentially strives to continuously improve the flow of value and reduce nonvalue-added activities. From the standpoint of a recent lean engineering implementation, the basic elements of lean include the definition of value, identification of the value stream, identification and elimination of barriers to increase flow, evolution towards customer pull, and continuous improvement or evolution towards perfection (http://www.isixsigma.com/dictionary/Littles_Law-690.htm).

According to Womack and Jones (2003), all work can be classified as either value added (VA), nonvalue added (NVA), or required nonvalue added (RNVA) (the latter two being called either waste or "muda").

Walton (1999) defines value in product development as "the right information product delivered at the right time to downstream processes/customers." Walton indicates that opportunities for improvement exist in cycle time, degree of product satisfying customer requirements, and ease of production, and he quotes benefits such as new product introduction cycle time down 30%, postcertification engineering change percent down 75%–96%, parts reduction, and first article inspection passed increased from 35% to 72% resulting from lean engineering implementation.

Walton (1999) discussed the product development process, particularly the requirements generation and needs identified through marketing, and the ensuing required resource prioritization. He points out that requirements generation is the most influential step of development with respect to the eventual success of the program, as 85% of life cycle cost is committed before the product analyzed entered full-scale development.

McManus (2005) proposed the following high-level objectives for lean engineering: creating the right product with efficient engineering processes and with effective life cycle and enterprise integration.

Right product/job

Developing the right product is a basic requirement to start with, as all engineering and development efforts that end up not answering customer needs or creating attractive market opportunities in the right products can be considered waste.

Wirthlin (2000) discusses improvements required in the fuzzy front end of product development, in the period during which requirements are captured and alternative concepts generated. He suggests an idealized set of best practices and proposes a set of over 40 questions centred around the notions of requirements identification, concept development, enablers, process, and business case to compare the current practice of an engineering organization involved in development activities versus best in class organizations.

Efficient engineering processes

As McManus (2005) highlights, LAI research suggests that to satisfy regulatory, safety, and quality concerns and allow for the management of complex aerospace systems, formal processes are required for almost all aerospace engineering activities. However, such processes are generally poorly defined, refer to obsolete practices that are not relevant to most jobs, miss key practices, and contain practices that have become irrelevant over time, and as a result are inconsistently followed.

McManus (2005) indicates that an assessment of engineering time card hours results in a whopping 40% pure waste, 29% necessary waste (i.e., setup or regulatory requirements), and only 31% added value. Interestingly, he then states that tracked, work package jobs are idle 62% of the time and active only 38% of the time. The combined value-added and job active percentage is thus about only 12%. He then discusses Kaizen improvement events, showing that 75%–90% of job idle time is spent at the bottleneck process, hence the focus of this paper on scheduling the bottleneck resources. Indirect measurements of job idle time though a metric called touch time ratio (TTR) (ratio of touch days divided by lead time) in company X supports the findings of McManus, as the average TTR varies in the range between 10% and 25%.

Effective life cycle integration

As stated earlier, in the lean enterprise, value is specified by the customer (usually captured through job tickets, voice of the customer approach, and quality function deployment (QFD) and flowed down using high-level program deliverable objectives).

Thus, the enterprise, as a going concern, must develop and offer in the marketplace products and (or) services of sufficient value (www.scav-csva.org) or features to justify their price. Given that 60%–80% of value is outsourced to various supply chain partners (McManus, 2005), these firms must be involved early in the engineering of the product in a concurrent fashion so as to leverage their experience and ideas, given costly changes that might be required otherwise, if key aspects of manufacturability or testability have been overlooked.

Production planning preparation (3P) events, involving representatives from all members of the supply chain involved in the coordination and delivery of value in new product development, have been used successfully in simulating the physical flow of goods and information. These 3P events have become an instrumental tool in enabling an unprecedented level of production in the assembly of aircraft engines (www.eclipseaviation.com/index.php?option=com_newsroom&task=viewarticle&id=1023&Itemid=51).

As the concepts that best meet customer needs are gradually defined, there is a need for conducting tradeoff studies to gradually refine and optimize the value proposition.

Lean business model

Let us now examine a lean engineering business model developed over the course of 2 years at a major aerospace engine manufacturer. The model compares key dimensions of engineering jobs outputted either in aggregate or at the individual level to some previously established baseline, at specific points in their life cycle in the engineering system.

As pointed out by Taylor (2005), it is difficult to assess the benefits of lean without such models, as the changes taking place are more of an evolutionary and gradual nature than those resulting from a drastic reengineering of operations. For example, waste reduction of 5% could hardly be felt by anyone. As it represents 5% of a 40 h week, this would only be 2 h of a person's time for that week.

This type of model, like any regular enterprise accounting system, is run every month to capture previous engineering system status and provide a high-level view of the progress achieved towards throughput improvement, waste elimination, and lead-time reduction. It starts by capturing the number of jobs completed at some predetermined stage of their life cycle in a given time frame (n). Job completion is determined through confirmation of specific activities in the work breakdown structure (WBS). For each such completed job, the evaluation of job lead time is performed by comparing the date of the first hour charged to the date of the last hour charged. In a similar fashion, the total amount of hours charged on each completed job is the sum of charged hours within that activity. The evaluation of average job lead time is performed together with the average charged hours using the previous values. Average job lead time is calculated as

$$\overline{\mathrm{LT}} = \sum_{i=1}^{n} (F_i - S_i) / 1.4n \qquad i = 1, \ldots, n \text{ jobs}$$

where $\overline{\mathrm{LT}}$ is the average lead time; F_i is the date of the last hour charged; S_i is the date of the first hour charged; and $i = 1, \ldots, n$ represents the number of completed jobs during the period of interest. The factor of 1.4 is required to convert lead time durations from a 7 days per calendar week basis to a 5 days per working week basis. Average charged hours is calculated as

$$\overline{\mathrm{CHRS}} = \sum_{i=1}^{n} \sum_{j=1}^{m} \mathrm{CHRS}_{ij} / n \qquad j = 1, \ldots, m \text{ days}$$

where $\overline{\mathrm{CHRS}}_{ij}$ represents the hours charged on job i during lead time by any node (or employee) k.

Based on an assessment of whether anyone has been charging more than a given threshold of hours on a given day on a specific job, each lead time day of a given design job is coded as either a touch day or alternatively a nontouch day. This means that if according to the rule given as follows, sufficient focus has been put on the job to have it progress, that day can be considered a day that helped progress the job towards completion. A predetermined threshold is such that more than 2 h must be spent during a day by at least one employee for that day to become a touch day for that job. The average number of touch days is calculated as

$$\overline{\mathrm{TD}} = \sum_{i=1}^{n} \sum_{j=1}^{m} \mathrm{TD}_{ij} / n$$

where TD_{ij} is a boolean variable representing touch days on job i on day j ($\mathrm{TD}_{ij} = 1$ if $\mathrm{CHRS}_{ij} \geq 2$ for any node k; otherwise, $\mathrm{TD}_{ij} = 0$). The average number of nontouch days is calculated as

$$\overline{\mathrm{NTD}} = \overline{\mathrm{LT}} - \overline{\mathrm{TD}}$$

where $\overline{\mathrm{NTD}}$ represents the average number of nontouch days.

The average number of nodes is simply the average of the number of employees that have been charging each design job:

$$\overline{N} = \sum_{i=1}^{n} N_i / n$$

where N_i represents the number of employees that have been charging to job i.

The number of hours delivered corresponds to the average hours previously discussed multiplied by the number of jobs completed in the chosen period:

$$\mathrm{HRD} = \overline{\mathrm{CHRS}} \times n$$

where HRD represents the number of hours delivered.

The touch time ratio is the ratio of touch days to lead time and effectively enables an evaluation of the effectiveness with which the lead time is used, with a low touch time ratio potentially indicating possible improvements in the flow of information and resulting reduction of waste:

$$\mathrm{TTR} = \overline{\mathrm{TD}} / \overline{\mathrm{LT}}$$

where TTR is the touch time ratio metric discussed previously.

The intellectual work in progress (IWIP) provides a snapshot of the level of intellectual inventory for jobs that have not yet been incorporated into a product (i.e., active jobs). As an example, the longer the lead time period during which the average engineering job is progressing, but not yet completed, the larger the amount of IWIP.

As for a regular supply chain, the following relationship holds:

$$\mathrm{WIP} = TL$$

where WIP is the work in progress, T is the throughput, and L is the lead time (www.isixsigma.com/dictionary/Littles_Law-690.htm). Commonly called Little's Law, we can see that a larger lead time L will be generating a larger amount of WIP. From this model it is obvious that to reduce the amount of WIP, one has to decrease the average job lead time (or increase the TTR).

As in the case of production, reducing levels of inventory in the intellectual engineering process is important, as the funds released from inventory reduction can be used in a much more profitable manner delivering additional value to customers and shareholders. The total amount of intellectual work in progress is calculated as

$$\mathrm{IWIP} = \sum_{i'=1}^{n'} \sum_{j'=1}^{m'} \mathrm{WHRS}_{i'j'}$$

where IWIP represents the total amount of intellectual work in progress at the end of a given period; and $\mathrm{WHRS}_{i'j'}$ gives the work in progress hours for an active, noncompleted job i' provided by employee j'.

Next, the calculation of the percentage of waste improvement is performed. Based on a subjective evaluation, 2 h of setup are allocated to each person that charges to the job (nodes):

$$\overline{\mathrm{SETUP}} = 2\overline{N}$$

where $\overline{\text{SETUP}}$ represents the average setup time, and $\overline{N}$ represents the average number of nodes that have been charging to the job.

Another 2 h of restart is added for each person that had a period of more than 2 weeks of inactivity on a given job and comes back charged to the job after this period. The average restart time is calculated as

$$\overline{\text{RSTRT}} = 2\sum_{i=1}^{n}\sum_{j=1}^{m}\text{RSTRT}_{ij} / n$$

where $\text{RSTRT}_{ij} = 1$ for any non-overlapping period of 10 days or more without charges from node k on job i; otherwise, $\text{RSTRT}_{ij} = 0$.

Lastly, the sum of hours charged on nontouch days is aggregated and averaged under the nomenclature of wasted setup (in the sense that these were not sufficient hours to significantly advance the job; thus, the time charged was probably wasted):

$$\overline{\text{WSETUP}} = \sum_{i=1}^{n}\sum_{j=1}^{m}\text{CHRS}_{ij}(1-\text{TD}_{ij}) / n$$

where $\overline{\text{WSETUP}}$ represents the average wasted setup.

Adding the three categories of waste given previously and dividing by the average charged hours provides for the percentage waste:

$$\overline{\text{WPCY}} = 100(\overline{\text{SETUP}} + \overline{\text{RSTRT}} + \overline{\text{WSETUP}}) / \overline{\text{CHRS}}$$

The percentage waste improvement is simply the difference between the baseline and year-to-date (YTD) percent waste values:

$$\overline{\text{WPCI}} = \overline{\text{WPCY}} - \overline{\text{WPCB}}$$

where $\overline{\text{WPCB}}$ is the waste percentage baseline, a value that has been established through analysis of the engineering system over previous periods; and $\overline{\text{WPCI}}$ is the waste percentage improvement.

YTD throughput improvement hours result from the comparison of prorated baseline throughput hours to a year-to-date cumulative value:

$$\text{TI} = T_{\text{Y}} - T_{\text{B}}(M/12)$$

where T_{Y} is the year-to-date throughput, T_{B} is the baseline throughput, M is the month, and TI is the throughput improvement.

The main dimensions of lean engineering savings include lead time reduction, throughput improvement, waste reduction, and reduction of inventory of intellectual work in progress (IWIP). All savings calculations use a notional hourly engineering rate R.

Lead time reduction is composed of two main components, the first one being a reduction in carrying cost for intellectual inventory resulting from the reduction in nontouch days, and the second resulting from a lead time delta from a prorated baseline.

As indicated previously, carrying intellectual inventory requires financing, as the potential revenues from selling the inventory will not be generated until some later time period, although employees are getting paid every 2 weeks. Thus, the concept of weighted average cost of capital (WACC), or more simply carrying cost (cc), can be used to determine the magnitude of the financing required for the intellectual inventory. Components of WACC include items such as cost of equity, cost of borrowing, risk levels, and the firm's beta. The reduction in carrying cost for intellectual inventory resulting from the reduction in nontouch days is calculated as

$$\text{LTR}_{\text{NTD}} = \text{cc} \times M(\overline{\text{NTD}}_{\text{B}} - \overline{\text{NTD}}_{\text{Y}})\text{IWIP} \times R/12$$

where $\overline{\text{NTD}}_{\text{B}}$ and $\overline{\text{NTD}}_{\text{Y}}$ represent the non-touch days for the baseline and year-to-date periods, respectively; R is the hourly rate over which the carrying cost cc is applied; and M is the number of time periods for the year to date.

The second component of the saving results in the value of a one-time output differential resulting from a lead time delta from a prorated baseline:

$$\text{LTR}_{\text{LT}} = R(\overline{\text{LT}}_{\text{B}} - \overline{\text{LT}}_{\text{Y}})\text{TI}$$

where $\overline{\text{LT}}_{\text{B}}$ and $\overline{\text{LT}}_{\text{Y}}$ represent the baseline and year-to-date lead time, respectively; LTR_{LT} is the saving associated with a reduction in lead time; and TI is the throughput improvement calculated earlier.

As mentioned earlier, the lead time reduction (LTR) is made up of two components, a reduction arising from a decrease in nontouch days and a reduction arising due to a reduction of lead time impacting throughput:

$$\text{LTR} = \text{LTR}_{\text{NTD}} + \text{LTR}_{\text{LT}}$$

Intellectual inventory reduction is carried on a 3 month rolling average basis with the reduction arising from the differential of carrying cost between baseline and year-to-date IWIP figures:

$$\text{IR} = \text{cc} \times R[(\text{IWIP}_{\text{B}} \times M/12) - \text{IWIP}_{\text{Y}}]$$

where IR is the value of the inventory reduction; and IWIP_{B} and IWIP_{Y} represent the baseline and year-to-date amount of intellectual inventory, respectively.

Waste reduction is calculated as

$$\text{WR} = \overline{\text{WPCI}} \times \text{HRD}_{\text{y}} \times R$$

where WR is the waste reduction calculated as the waste percent improvement times the hours delivered to date (HRD_y) times the applicable hourly rate.

Lastly, throughput improvement is calculated as 50% of the difference between a prorated baseline throughput and the year-to-date throughput:

$$TS = 0.5TI \times R$$

Lean savings (LS) is simply the sum of the lead time reduction, inventory reduction, and throughput improvement savings:

$$LS = LTR + IR + WR + TS$$

Lean logistics methodology

Once the engineering value stream has been identified, using the approach outlined in Braglia et al. (2006) and Rother et al. (2003), the proposed lean logistics methodology is performed in five steps: (*i*) identify demand, (*ii*) determine the value stream of the bottleneck and perform current and future state value stream mapping, (*iii*) plan and schedule jobs at the bottleneck operation, (*iv*) coordinate job release with the bottleneck, and (*v*) measure performance at the bottleneck and implement improvements as required.

Identify demand

The first step is to identify demand. The engineering planning organization must take into consideration the upcoming identified demand, budgeted or not, originating from different organizations, for either support to other organizations (i.e., operations, marketing, customer service, etc.), post-engine certification activities, or new product development jobs, and aggregate it for various skill types.

Some of these jobs may have been known in advance and thus may have been forecasted. Some may already have been worked on and possess an estimate to completion (ETC) together with a forecasted completion date, whereas others called “walk-ins” may be more difficult to predict in advance in terms of magnitude and timing of occurrence (i.e., safety and reliability, aircraft on ground, etc.). It is also possible to have a forecasted demand still at a planning stage, i.e., higher level than job level. Obviously, as indicated by Silver et al. (1998) in a production environment, one would expect that in the short term the level of released orders would account for a bigger proportion of the demand than planned orders, and for a significant proportion of the overall bottleneck capacity. The same rationale would apply here for engineering jobs.

To account for unforeseen demand, a good practice is to reserve capacity by specifying in a corporate policy a planned maximum utilization percentage of resources consistent with expected walk-in levels, service level expectations, job lead time, and intellectual inventory objectives. This practice effectively allows for a certain percentage of resources being available for unplanned tasks and can also cover activities of a more recurrent nature (i.e., daily investigation of quality notifications, etc.).

Determination and improvement of the bottleneck value stream

The second step is the determination of the engineering value stream bottleneck and performance of current and future state mapping. The bottleneck determination is for the time horizon under consideration. The Goldratt and Cox (2004) theory of constraints approach and value stream mapping (VSM) current practice (Rother et al., 2003) suggest focusing on the pacemaking operation both in terms of scheduling and in terms of improvements. Value stream mapping workshops in which Kaizen burst type activities are performed have repeatedly shown excellent results when using group decision making techniques, such as Open Space, as suggested by Owen (1997). Cooperrider et al. (2008) developed an approach called appreciative inquiry, and its four steps of discovery, dream, define, and destiny can be used to generate the vision of the ideal state and the steps towards achieving it.

As indicated by Silver et al. (1998), in a typical production job shop, bottlenecks are frequently shifting, and the same is assumed for the engineering system, due to the changing mix and maturity of projects and other activities. Care must thus be exercised to confirm that for the next iteration of the aggregate planning process the location of the maximum demand over capacity ratio (i.e., the bottleneck) remained where it was believed to be located:

$$\mathrm{Max}\left(\frac{\sum \mathrm{DEM}_j}{\sum \mathrm{RES}_i}\right)$$

where $j = 1, \ldots, n$ jobs; $i = 1, \ldots, e$ employees; DEM_j is the demand of design job j denominated in the base period; and RES_i is the capacity of employee i of critical skill in terms of the base period. The base period can be days, weeks, or months, with the algorithm being reproduced at every n periods (say every 1–4 weeks) over a rolling horizon of m periods (say 3–6 months).

The determination of the bottleneck skill is performed outside of the optimization model referred to in this paper. This determination can be easily performed on a spreadsheet or via project management software.

Note that in the model provided, dummy resources are added to the model to account for the likely scenario that higher demand than available capacity exists for the bottleneck skill.

Proactive logistics: plan and schedule jobs

The third step is the planning and scheduling of jobs considering bottleneck skills. During planning, the assigning of scarce resources needs to be performed in a manner that will ensure the completion of a maximum of high-priority jobs (i.e., no remaining forecast or ETC at the end of the planning

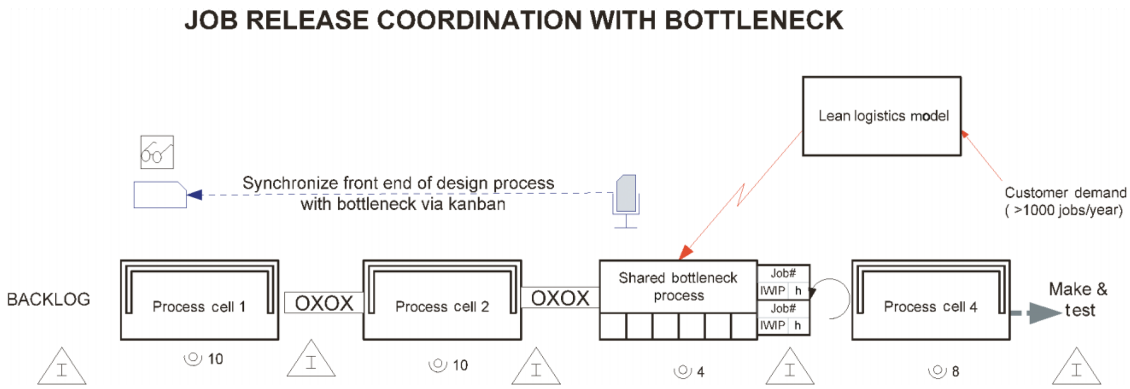

Figure 1. Reactive logistics: pacemaking, synchronized engineering value stream.

horizon). Higher costs are incurred if a complex job is handed over to a lower skilled employee or if the job cannot be completed within the current period. For each person (node) touching the job, there is also an assumed setup cost of 2 h added to the total cost, as assumed in the lean engineering business model. The model attempts to maximize the number of jobs completed, given priorities and other considerations.

Job scheduling over the planning horizon is performed next. Shortest processing time (SPT) sequencing for the single machine case has been shown to minimize a number of interesting characteristics from a lean standpoint, such as the total and mean flow time, the mean waiting time, and the mean and total lateness. Earliest due date (EDD) heuristics only minimize maximum lateness, and as such are less attractive from a lean standpoint where the one objective is to reduce IWIP.

Some logistical issues may arise, however, as the bottleneck may not be located at the first operation of the value stream. In addition, forecast accuracy and firm forecast visibility need to be at sufficient levels to sequence jobs properly (Van Koten and Gray, 2005) so that the planning and scheduling system generates a sufficient degree of confidence in users and gains adequate acceptance.

Reactive logistic: coordinate job starts with the bottleneck

The fourth step relates to the coordination of the value stream up to the bottleneck skill area. Given the discrete nature of design jobs, a synchronization mechanism must be established to help ensure that the started jobs requiring the bottleneck area expertise will have access to the required resources in the appropriate time frame. At the same time, coordinated decisions from the planning organization about the nature of jobs started at the beginning of the engineering value stream can improve flow, reduce average job lead time, and ensure a more effective use of other than the bottleneck resource by ensuring that jobs requiring other than the bottleneck resource are scheduled.

Techniques such as Heijunka boxes and signal Kanban can be used in the physical implementation of the lean engineering logistical rules to support the aforementioned objectives in an operational manner. **Figure 1** illustrates the use of Heijunka boxes.

Measure value stream performance

The fifth and last step involves the measurement of performance of the value stream on the dimensions previously discussed in the lean business model.

Proactive lean logistics model

As indicated earlier, a variety of models can be designed to help achieve a number of different objectives. In this section we present a model that enhances management decision making effectiveness, helping to decide which job to allocate to what resources, given the complexity inherent in managing in an optimal manner the allocation of scarce engineering resources to design jobs of varying nature, complexity, and priority.

The demand is conveyed through a number of jobs. For some of these jobs of interest here, scarce value stream bottleneck resources must be assigned. The key assumptions are as follows: (*i*) engineers (e) work sequentially, one design job (j) at a time; (*ii*) vacation time is considered for employees, such that their capacity is reduced for a given time horizon; (*iii*) scheduling is conducted over a rolling 3 months time period; (*iv*) applicable regulation must be considered in the assignment of jobs to engineers, to determine among others whether employees have adequate clearance given the nature of the design job (i.e., military); (*v*) job complexity versus employee proficiency is considered and used to modulate the initial estimate of resource required (forecast); (*vi*) different levels of job priority must be considered from field issues to operational priorities, cost reduction opportunities, new program development, and technology or process improvement; (*vii*) each engineer working on the design job incurs setup; and (*viii*) demand exceeds capacity.

The lean engineering logistics model variables are as follows: j is the design job; e is the engineer; x_{je} is the number of weeks spent by engineer e on design job j; $y_{je} = 1$ if $x > 0$, otherwise, $y_{je} = 0$; PR_j is the priority of job j; D_j is the demand

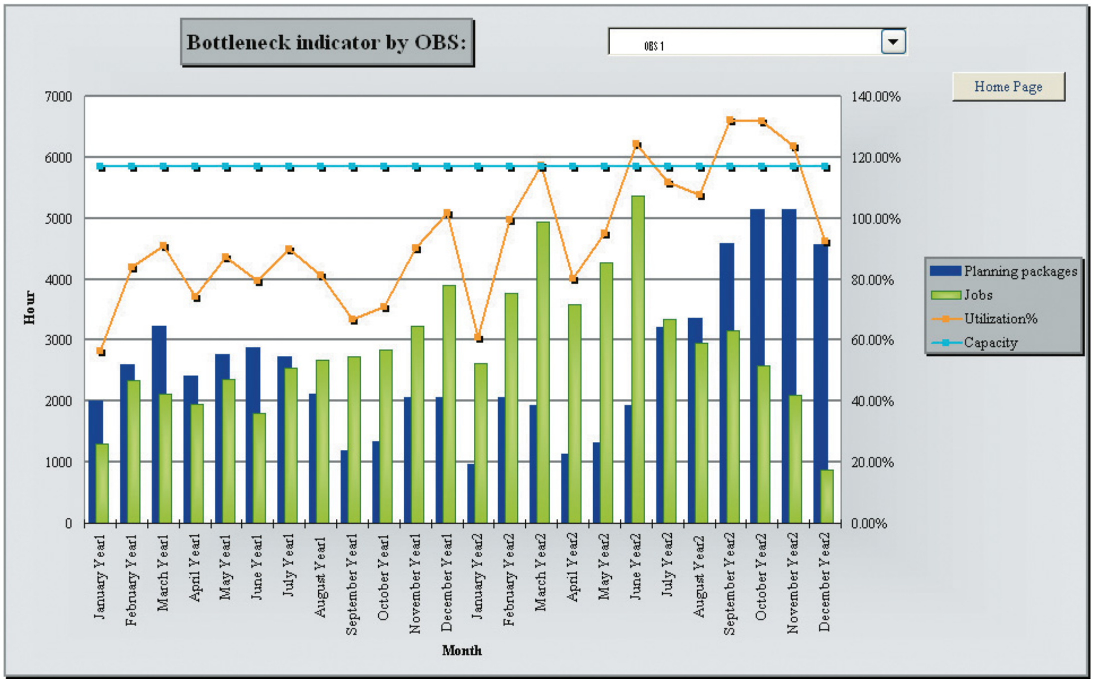

Figure 2. Identify demand.

of job j; C_e is the capacity of engineer e in the time horizon; CO_j is the complexity of job j (for low complexity, $CO_j = 1$; for high complexity, $CO_j = 2$); P_e is the proficiency of engineer e (for low proficiency, $P_e = 1$; for high proficiency, $P_e = 2$); V_{je} is the forecasted effort adjustment factor to consider an engineer's proficiency and the job complexity ($= P_e x_{je}/CO_j$) (note how the initial estimate is influenced by a ratio of difficulty to expertise) (Bashir and Thomson, 2004); S_j is the setup time for design job j; if job is military, $Z_j = 1$, otherwise, $Z_j = 1$; if employee is cleared, $CA_e = 1$, otherwise, $CA_e = 0$; and if the job j is completed, $OUT_j = 1$, otherwise, $OUT_j = 0$.

The objective of the lean logistic model is to support the lean engineering objective by maximizing the number of jobs completed (throughput) with priorities via scheduling of the most appropriate resources to jobs:

$$\text{Max} \sum_j \text{Out}_j \times \text{PR}_j$$

The following constraint is required to ensure that demand is met:

$$\sum_e V_{je} = D_j \text{Out}_j + \sum_e y_{je} S_j$$

The jobs being touched are identified as

$$x_{je} \leq M y_{je}$$

Regulation must be complied with:

$$y_{je} \leq 1 - Z_j + CA_e$$

Lastly, capacity restriction must be considered:

$$\sum_j (x_{je} + y_{je} S_j) \leq C_e$$

Results and analysis

In this section we review the results and learning from an ongoing implementation of the five steps in lean logistics methodology described previously.

Identify demand

Demand for engineering resources is captured via the P/S module of SAP, the enterprise resource planning system used by the engineering organization. Demand is initially captured for high-level planning packages following engineering cost estimation exercises. As detailed design activities are launched, further details are specified at the job level. A graphical interface to SAP P/S has been created to display demand, capacity, and utilization level for various engineering activities (organization breakdown structure, OBS). **Figure 2** provides an illustration of the approach that was implemented for identifying demand. Data have been masked to preserve confidentiality. For the engineering organization called OBS1, there is a monthly engineering capacity of about 6000 h. During year 1, the aggregated monthly demand arising from planning packages and jobs is well below the available capacity, resulting in a utilization level that does not exceed 100%, thus providing sufficient capacity to respond to unplanned events. During year 2, however, monthly utilization levels in excess of 120% indicate that this OBS could become a bottleneck if no improvements are made.

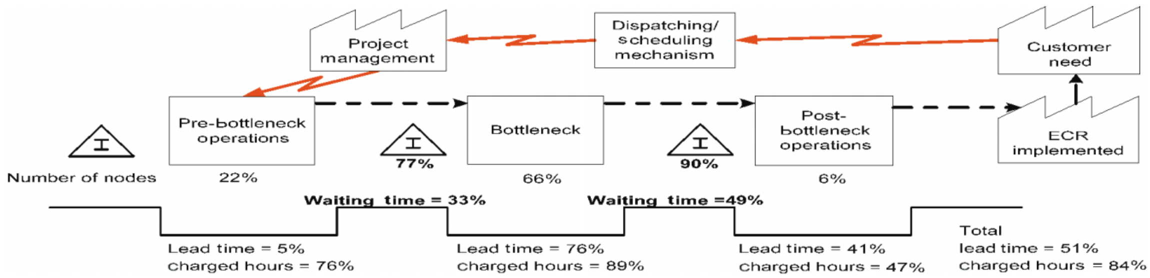

Figure 3. Value stream maps pre- and post-lean engineering implementation.

Determination and improvement of the bottleneck value stream

Value stream mapping is an important task within lean engineering. It enables not only the mapping of the present state, but also the determination of what the future state should be and the steps required to make it happen. However, defining and mapping the key engineering value stream is a difficult task. Extensive data analysis of the engineering jobs routing, sequence, effort, and lead time on key bottlenecks was performed. Available data show that routing, sequence, duration, and effort vary to a great extent among jobs. The nature of the engineering activities in product development requires improved value stream mapping techniques.

Leveraging the work from Braglia et al. (2006) on complex manufacturing systems, a matrix of n jobs known to have required the bottleneck resources identified in the previous step and m available engineering resource types (OBS) is formed, with a value of one indicating a given job using a given resource, and a value of zero indicating otherwise. Next, an $n \times n$ diagonal matrix of similarity values is created using the following equation:

$$S_{ij} = \frac{x_{ij} + \sqrt{x_{ij} y_{ij}}}{x_{ij} + x_i + x_j + \sqrt{x_{ij} y_{ij}}}$$

where $0 \leq S_{ij} \leq 1$ are pairwise similarity coefficients, x_{ij} is the number of OBS used by both job i and job j, x_i is the number of OBS used by job i only, x_j is the number of OBS used by job j only, and y_{ij} is the number of OBS not used by job i or job j. Clustering is then performed on the jobs that have similarity values above a given threshold. Out of the initial 225 jobs considered, the majority ended up being allocated to a short list of five families.

Current and future state value stream maps of key engineering job families were produced using the approach described earlier. As suggested in **Figure 3**, pre- to post-implementation percentage improvement achieved on key dimensions, for a given family, resulted in a lead time reduction of 51% and charged hours reduction of 84%. To generate such results, hybrid workshops facilitation techniques combining the approaches of Owen (1997) and Cooperrider et al. (2008) were used.

Proactive logistics: plan and schedule jobs

The proactive lean engineering logistics model has been tested during a lean engineering logistics training session through a game consisting of a simulated simplified dataset of 12 jobs and four engineers (see **Figure 4**). These jobs were considered for completion in the next 12 week time horizon. Job requirements indicated how many weeks of effort were required to complete the job. A job complexity value of 1 indicated a low-complexity job, whereas a value of 2 indicated a high-complexity job. Regulation (CGRP) of 1 indicated that a job could only be worked on by a resource having received appropriate clearance (i.e., CGRP value of 1 for the engineer), and a value of 0 would not pose any constraint on the type of personnel executing the job. A priority value of 1 was indicative of low priority, whereas a priority value of 3 suggested higher priority.

Proactive lean engineering logistics model results for the previous case-study dataset are provided in **Figure 5**. According to the model, a maximum of 11 out of the 12 jobs could be completed in the next planning horizon using the data provided. Each resource had a capacity of 12 weeks. All except resource 3 had CGRP clearance to work on regulated jobs. All resources except resource 2 had high proficiency.

In the case study performed, the highly proficient resource 1 completed low-complexity job 1 in 7.05 weeks, consistent with the model described in the previous section and with an effective setup time of 0.05 weeks.

These results were compared with the results obtained by teams of experienced project managers during a recent lean engineering and project management training session. Key differences between how teams scheduled design jobs have been observed during this training session. Teams used either due dates, processing time, job complexity, or type of job as a basis for scheduling, which gave rise to varying levels of performance when compared with the optimal model output. This experiment reinforces the idea that management decision support system (DSS) and prioritization tools would be required to improve the consistency and performance of lean engineering, proactive logistics decision making. **Figure 6** provides a good sequence that shows the order in which the 11 jobs could be performed.

Implementation of the proactive lean engineering logistics optimization model is progressing well, especially in value

Team ________

% Jobs Completed = 100* No. Jobs Completed / 12

Plan : number of weeks worked on job by employee

	Job #															
Employee #	1	2	3	4	5	6	7	8	9	10	11	12	Total	Cap	CGRP	PROF
1														12	1	2
2														11	1	1
3														12	0	2
4														12	1	2
Total wks allocated																
Job Requirement	14	6	4	8	2	4	2	8	2	2	2	2				
Job Complexity	1	2	2	1	1	2	1	2	1	2	2	2				1 low 2 high
Regulation (CGRP)	0	0	0	0	1	0	0	0	1	0	0	0				
Priority	3	2	1	2	1	1	3	3	1	1	2	3				1 low 3 high
Job Completed?													**12?**			

Figure 4. Lean engineering logistics game dataset.

				Good plan jobs												
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**TOTAL**
ETC (wks)				14	6	4	8	2	4	2	8	2	2	2	2	
complexity				1	2	2	1	1	2	1	2	1	2	2	2	
regulation				0	0	0	0	1	0	0	0	1	0	0	0	
priority				3	2	1	2	1	1	3	3	1	1	2	3	
Resource	**Proficiency**	**CAP**	**CGRP**	**VOL**												
1	2	12	1	7.05	3.98								0.98			**12**
2	1	11	1						8.1		0.5		2.25			**10.9**
3	2	12	0			4.05					7.85					**11.9**
4	2	12	1				4.03	1.03		1.03		1.03		2.05	2.05	**11.2**
	Completed			**1**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**11**

Figure 5. Optimal lean engineering logistics model results.

streams where the quality of data, as measured by a six sigma metric called defects per million opportunities (DPMO), is less than 80 000. Recommendations from Sipper and Bulfin (1997) suggest a minimum of 92% accuracy in enterprise resource planning (ERP) records such as bill of materials and inventory values for manufacturing implementations, such that the system produces believable and useful information. In a similar fashion, data from engineering value streams containing bottlenecks must possess a high level of accurate information before implementing the proactive engineering logistics approach. Potential items to consider for enabling the implementation of lean engineering logistics include addressing data defects, such as “missing ownership – projects or design,” “invalid forecast finish date – date in the past,” “no ETC in the resource screen,” and “no baseline” situations.

Reactive logistic: coordinate job starts with the bottleneck

Job- and resource-related coordination work to ensure the availability of bottleneck resources and align other OBS resources is currently taking place during weekly value stream review meetings. Through these reviews, much progress has been made improving information accuracy. The job start decision making via the single-stage Kanban pull system is not implemented yet. A potential reason for this is that as a need for engineering work is recognized, and relevant engineering jobs are created, these jobs get released and become available for engineers to work on immediately, i.e., they are de facto already released on the floor. The absence of a “backlog” place holder where engineering jobs would reside until a decision to have them pulled to be worked on next likely constitutes a key reason for this absence of job start coordination decision making.

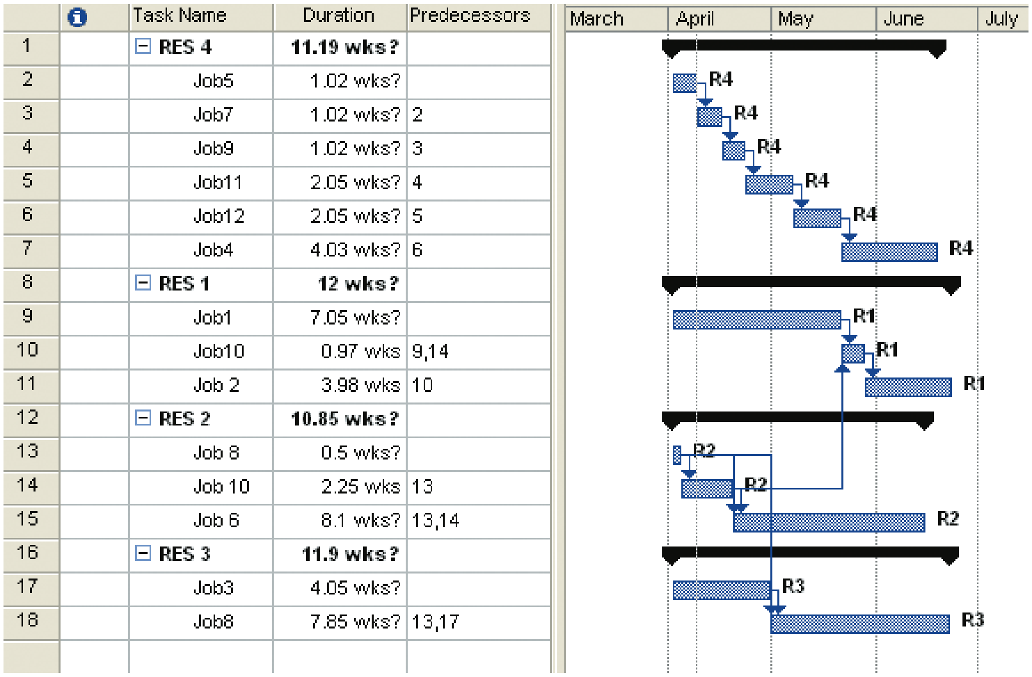

Figure 6. Reasonable schedule.

Discussion and opportunities for further research

Examination and analysis of the current levels of forecast visibility and accuracy have shown that additional work on improving the projected requirements would be beneficial before implementing the proactive lean engineering logistics model. Further work and research to support an improvement in forecast visibility and accuracy are thus suggested.

The implementation of an optimization model such as the one contemplated here relies on adequate visibility and accuracy of forecasted bottleneck resource requirements. As discussed earlier, extensive analysis has shown that material differences exist between design job forecast and actual resources expended. The proposed mixed integer – linear optimization model cannot handle such uncertain forecasts. Alternative stochastic DSS models should thus be developed to deal with this fuzzy environment.

Given the aforementioned consideration, a much simpler non-optimal logistical approach based on due dates has been implemented as a first step. It is expected that through this simpler first step, more adequate forecasted effort and better data maintenance will become available and will support the implementation of the proactive lean engineering model as a next step.

Effective control of job size, and number of jobs released to the engineering system, will help achieve more consistent and predictable engineering product development performance. Further work modeling key product development (PD) system performance parameters through discrete event simulation is in progress.

The idea of implementing reactive logistics concepts in a specific engineering bottleneck met some resistance. Some of that might be attributed to the lack of sharing and knowledge of documented successes in the implementation of Kanban-based approaches in the aerospace engineering area. Further research in this area would be required to improve awareness of potential benefits, known pitfalls, and difficulties in designing and operationalizing engineering production systems around these concepts.

A possible additional reason for the current lack of support of this reactive "lean-based" logistics approach may be related to the traditional functionally oriented organizational structure.

The current engineering structure is functionally oriented. The bottleneck organization being worked with is a service organization, supporting multiple core design functions. The current perception is that it is politically difficult for this organization to have a visible impact on the decision to start design jobs or not. As discussed earlier, further work evaluating the benefits associated with the implementation of a backlog stage in the engineering job release decision process is required.

Lastly, the presence of a silo approach and the absence of a value stream based management organization might be contributing factors to this situation. Some additional research work might be required to identify the ideal organizational structure conducive to improved operational engineering effectiveness and flow maximization.

Conclusion

Developing and implementing a methodology to optimize throughput in a bottleneck engineering operation, scheduling a work process downstream in the value chain to drive the start of resource expenditure upstream, and considering the availability of critical resources in time at the bottleneck operation to determine whether, when, and how to start jobs are worthwhile exercises that support customer satisfaction and increase shareholder value and employee satisfaction.

In this paper we reviewed the main dimensions of lean in engineering and provided a clear and workable financial model to demonstrate the benefits.

A new framework for implementing lean engineering in five steps has been presented, and the implications for practical application have been explained. Our work assumed that improved engineering logistics is made possible by an adequate planning and estimating ability.

We discussed proactive and reactive lean engineering logistics approaches. Lastly, we discussed various aspects of an ongoing implementation and reviewed key areas for further research.

Our work indicated the need for additional coordination in the engineering value stream and for support in decision making about which job to execute, given the complexity of the decisions to be made.

Building a more efficient and proactive engineering organization is possible. By integrating notions of production and inventory management with lean, we have offered a coherent logistics approach to support lean promises.

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