# Supply Chain Measures of Performance for Wood Products Manufacturing

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**Abstract**

This article reports the results from a supply chain study in which a performance measurement system for a wood products value stream was developed. We build on findings from a previous study in which the need for supply chain metrics of performance was identified. A five-step method to develop performance measures is suggested as an improvement alternative. Examples of specific metrics for quality and time performance are provided. This approach facilitates collaboration between supply chain partners and provides information that allows a more efficient focus on improvement projects. Supply chain measures of performance are important for seeing beyond a single entity and aligning strategy in the supply chain. Companies that want to integrate their suppliers and customers in their improvement efforts can benefit from the information presented here, because a common set of performance measures is essential in evaluating progress toward a goal.

Supply chain management (SCM) has received a great deal of attention from researchers and practitioners during the last decade. According to the Council of Supply Chain Management Professionals (2010), SCM ''encompasses the planning and management of all activities in sourcing, conversion, and logistics; and includes also the coordination and collaboration with supply chain partners, which can be suppliers, intermediaries, third-party service providers, and customers'' (p. 618). The fall of trade barriers, innovations in transportation and information technologies, deregulation, and improvement in logistics management are all factors in the emergence of SCM. According to the SCM point of view, companies must closely integrate and collaborate with their suppliers and customers in aspects like logistics, information, quality management, and process flow management. The importance and benefits of this approach have been extensively documented (Towill 1996, Mason-Jones and Towill 1997, Berry et al. 1999, Tan et al. 1999, Lambert and Cooper 2000, Petersen et al. 2005). For example, SCM practices have been found to be associated with superior product quality, delivery reliability, process flexibility, cost leadership, and higher levels of design and conformance quality (Rosenzweig et al. 2003, Fynes et al. 2005).

Similarly, a tough competitive environment has driven many organizations to start continuous improvement programs to remain competitive in a global market. Several approaches have been proposed and implemented, but particularly popular among US manufacturers are the lean manufacturing and Six Sigma improvement philosophies (Blanchard 2006). Six Sigma is an improvement methodology that focuses on extensive data collection and use of statistical tools to eliminate defects and reduce variation, thus achieving customer satisfaction (Chung et al. 2008). Lean manufacturing focuses on eliminating manufacturing waste[1] and increasing manufacturing flexibility to generate the greatest value for the customer (Goldsby and Martichenko 2005, Raisinghani et al. 2005). Regardless of the method adopted, an essential component of any continuous improvement program is an effective performance mea-

[1] Waste in this context is understood as any activity that does not add value to the product from the customer's point of view. Examples of waste are overproduction, unnecessary movements or transportation steps, and defects.

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surement system. Advances in information technology have greatly facilitated the timely transfer of data to keep measures up-to-date, often in real time. It has even become common for large organizations to maintain corporate ''dashboards,'' which are visual displays of the most important information about an organization's performance that can be monitored at a glance.

Some challenges when designing performance measurement systems are (1) having a balanced set of metrics, including all relevant metrics; (2) aligning metrics with strategic goals; (3) avoiding metrics that drive wrong behaviors; (4) facilitating access to required information; and (5) ensuring the measurability of data (Beamon 1999, Bourne et al. 2002, Van Aken and Coleman 2002). Performance measurement in a supply chain (SC) environment presents additional challenges. SCs are larger and more complex systems and overall measures should be consistent with each component's strategic goals. Performance measurement systems are key elements of SC collaboration, because metrics drive behavior and, to be meaningful, measures must be common across the SC members (Simatupang and Sridharan 2008). Several approaches for SC performance measurement have been proposed. Some authors favor having only a few simple measures for SC performance, like *product availability* and *total SC costs* (Lapide 2000); the *perfect order,* or the percentage of orders meeting the customer's expectation perfectly (Novack and Thomas 2004); or focusing on time compression, thus reducing the *lead time* (Towill 1996). Other authors state that a good performance measurement system for SCs should include metrics for all relevant aspect of performance. According to Beamon (1999), performance measures used for an SC should reflect *resources, outputs,* and *flexibility,* and in fact, Beamon listed a set of 18 specific measures of performance. Li et al. (2005) developed a questionnaire-based measurement instrument to assess overall SCM performance, grouping SCM practices in six categories: (1) strategic supplier partnership, (2) customer relationship, (3) information sharing, (4) information quality, (5) internal lean practices, and (6) postponement. Kaplan and Norton's balanced scorecard (Kaplan and Norton 1992) has also been suggested to measure SC performance, using the same dimensions of performance but different measures (Brewer and Speh 2000).

Most US wood products companies have not yet leveraged the benefits of SCM (Buehlmann 2004) like reduced total costs and shortened lead times (Towill 1996, Mason-Jones and Towill 1997, Berry et al. 1999, Tan et al. 1999, Lambert and Cooper 2000, Petersen et al. 2005). Research has been reported regarding SCM in the wood products industry (Simpson and Wren 1997, Fontenot et al. 1998, Vlosky et al. 1998, Buehlmann 2004, D'Amours et al. 2004, Carlsson and Rönnqvist 2005, Beaudoin et al. 2007, Frayret et al. 2007, D'Amours et al. 2008, Sasmohapatra 2009), but the development and implementation of performance measurement systems in wood products SCs has received little attention. As more companies in the industry integrate their suppliers and customers into their business processes, however, the need to include SC partners in their performance measurement system will increase.

An SC study reported by Espinoza et al. (2010) in a specific wood products value stream revealed a need to develop SC measures of performance. The present research builds on the results presented in the above-mentioned study and on supply chain performance measurement research by suggesting a methodology that companies can use to develop or improve their own performance measurement system. The objective of the present study was to develop a performance measurement system for a wood products SC. While businesses collect and report performance information in areas like finances, quality, human resources, customer satisfaction, and operational performance that are internally focused on a specific business unit, this study focused on product quality and time performance measurement through several business units in the entire SC.

## Methodology

An in-depth case study carried out by Espinoza et al. (2010) in a wood products SC found that although the focal company of the study had implemented a corporate performance reporting system, that system was internally focused, with metrics being reported for individual plants operated by the company and, thus, not reflecting the relative contribution of each plant to the overall performance, as is necessary for an effective SC performance measurement system (Chan et al. 2003). Furthermore, external suppliers were not included in this performance measurement system, which therefore did not capture performance across the entire SC (Lambert and Pohlen 2001). Although the metrics used internally were instrumental in identifying and correcting defects at each establishment, they did not facilitate the rapid identification of causes when these originated farther upstream in the SC. Last, quality performance information was shared only with the immediate SC partners. This need was addressed by suggesting a performance measurement system for the mentioned SC.

The need for SC performance measurement was explained by Lambert and Pohlen (2001) as the need to (1) go beyond internal measures, expanding the line of sight from a single entity to the overall SC network, (2) align strategy and activities in the SC, (3) achieve differentiation to gain competitive advantage, and (4) encourage cooperative behavior between SC members. The SC measures of performance span the entire SC, and they reflect quality across all entities and the contributions of each component to the overall performance.

The development process of SC quality measures in the present study (Fig. 1) was based on methodologies proposed

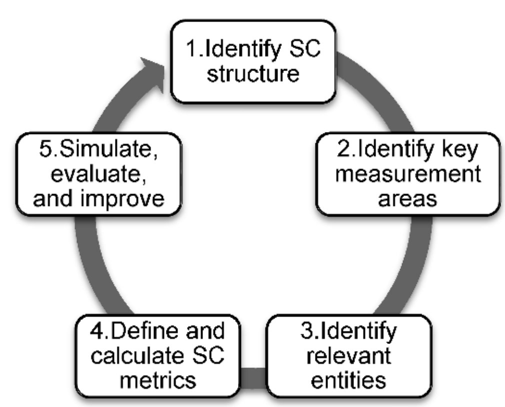


*Figure 1.—Development process for supply chain quality measures.*

by Van Aken and Coleman (2002), Lambert and Pohlen (2001), and Dasgupta (2003). The first step in the development process consists of identifying the SC structure—basically, the SC components, material flows, and information flows. This was accomplished following the process suggested by Jones and Womack (2002)—namely, to map a value stream where a product component was followed throughout its transformation and supply process, from lumber manufacturing to final delivery at the end-user's home. Second, the critical performance areas in which the SC must excel to achieve customer satisfaction are recognized. Critical factors of quality for each performance area are also identified. Third, the SC entities relevant to the performance to be measured are identified. For example, the measurement of responsiveness (the ability of an SC to react quickly and cost-effectively to shifts in customer needs) may include third-party logistics providers. However, these third-party logistics providers might not be as relevant when measuring tangible dimensions of product quality, such as color consistency. Fourth, the SC measures are defined and calculated. Finally, the system is simulated to test its robustness and sensitivity, and changes are made as necessary. The simulation was carried out using a Monte Carlo approach in an electronic spreadsheet environment.

## Results and Analysis

### SC structure

The first step in any SC study is to learn about the structure of the system (Lambert and Pohlen 2001), which basically includes SC components, material flows, and information flows. The extended value stream map in Figure 2 shows a simplified view of the SC structure: flow of materials typically runs from left to right, and information flows in the opposite direction in the form of customer orders. The company in this study uses a centralized scheduling system, which receives orders from the retailer and sends them back to the company's facilities. The facility that manufactures product components (hereafter referred to as the components plant) places orders to lumber suppliers on a monthly basis. Operations scheduling is demand driven from the retailer to the assembly plant, meaning that production happens only based on firm orders. From the assembly plant to the lumber supplier, however, production is scheduled mainly based on forecast and on replenishing stocks of parts and subassemblies. While beyond the scope of this article, value stream maps can also detail the processing steps and times, defect rates, inventory size and location, and transportation links for every operation within all business units in the SC (more detailed information about this topic can be found in Espinoza 2009).

### Key performance areas and relevant entities

Two key performance areas were selected for an initial benchmarking of the SC: logistics and product quality performance. The former can be measured by how effectively the SC is delivering defect-free products in a timely manner (time performance). In addition to manufacturers and retailers, transportation operations should be included when evaluating logistics performance. Product quality performance can be measured by the defect rate at each step of the transformation process, and the relevant entities would include manufacturing facilities and providers of installation services. Figure 3 shows the specific metrics of concern at each business entity measuring time and product quality performance.

### Performance SC metrics

As for performance metrics, the system proposed uses Six Sigma measures of performance. Although limited in number, some studies have explored the use of Six Sigma to measure SC quality performance. Dasgupta (2003) mentioned that the major advantage of this approach is that Six Sigma metrics allow comparison between processes on the same scale, irrespective of their nature (manufacturing or service processes) or complexity (few or many parts). Such comparisons are critical when gauging the performance and alignment of businesses in their SC environment. Six Sigma has also been suggested for supplier evaluation (Wang et al. 2004) by developing a ‘‘performance score’’ based on principal component analysis. Customer satisfaction can be measured using Six Sigma metrics as well; Fontenot et al. (1994) suggested using data from a customer satisfaction survey to calculate Six Sigma measures such as defect rate (proportion of unsatisfied customers). Those authors stated that customer satisfaction is truly a multistage

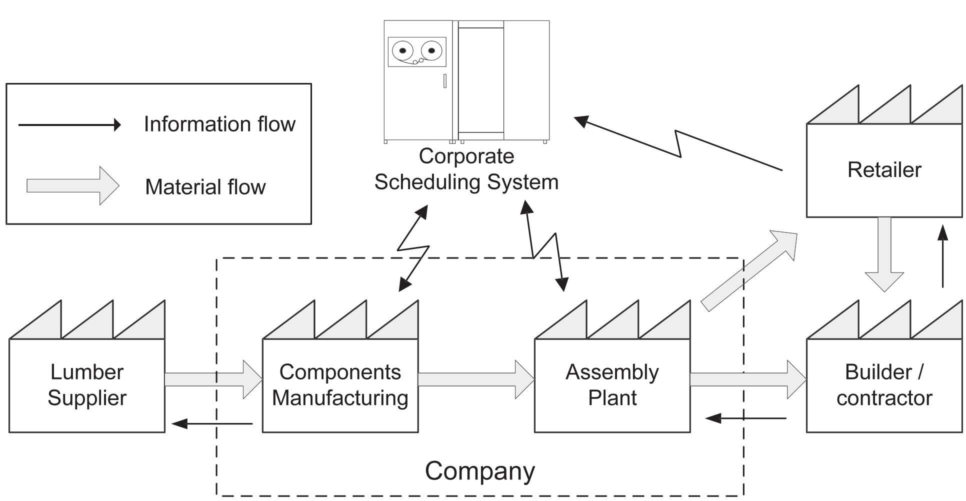


*Figure 2.—Simplified view of the structure for the supply chain studied.*

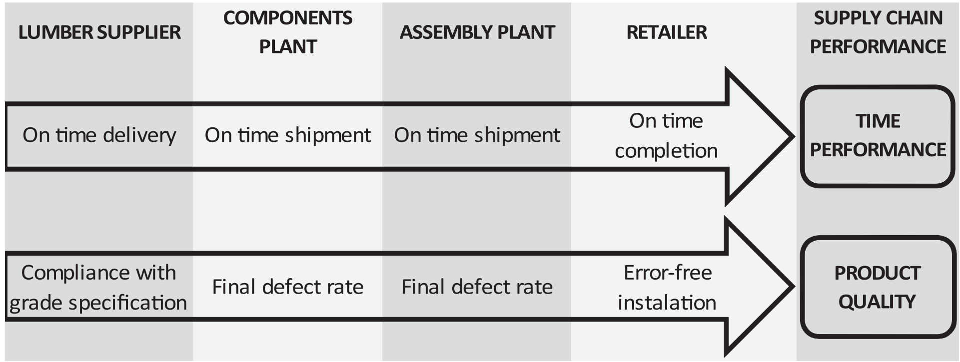


*Figure 3.—Relevant entities to measure time performance (top) and product quality (bottom).*

process, because it results from the actions taken at all steps before the product or service reaches the customer. Last, Graves (2001) presented a discussion of the value of using rolled throughput yield (RTY) in situations where different types of products and/or services are compared. A major advantage of RTY is that it considers the contributing losses at all steps in the transformation process, not only the final result. RTY facilitates the process of selecting those improvement projects that will have the most impact on overall quality improvement and cost reduction. The measures of performances included in the proposed system and their computation are listed in Table 1.

It is very important to put in writing clear definitions of quality in the form of precise performance measures. Table 2 shows this information for each stage in the SC.

Once the measures of performance were selected, quality performance measures were calculated using historical data for the case study. Figure 4 shows the resulting performance measures for product quality. Specifically, Figure 4a shows defect rate and sigma score for each SC component and for the overall SC. Defect rate is measured as the ratio between the number of observed defects and the opportunities for a defect, usually expressed on a per-million basis (Table 1, Eqs. 1 and 2). Sigma score reflects the number of standard deviations that can fit between the average of the process and the specification limit (Table 1, Eq. 5). A higher sigma score indicates a more capable process. A sigma score of six is the ultimate goal of the Six Sigma philosophy and is equivalent to a defect rate of 3.4 defects per million opportunities. In the example, the SC performed at a 2.9 sigma level over the period or analysis. Sigma score can be used by an organization when setting its performance improvement targets. For example, a company that is currently performing at a 3.0 sigma level might target achieving a 5.0 level in 5 years (60 mo). Closing this ‘‘performance gap’’ would translate into a compound

*Table 1.—Summary of supply chain performance measures.*

| Performance measure | Equation | Where |
|---|---|---|
| (1) Defect rate per opportunity (DPO) | $\text{DPO} = \frac{d}{p \times n}$ | $d$ = number of defects observed<br>$p$ = opportunities for defects in a product unit[a]<br>$n$ = product sample size |
| (2) Defect rate per million opportunities (DPMO) | $\text{DPMO} = \text{DPO} \times 10^6$ | DPO = observed defects per opportunity |
| (3) First-time yield (FTY)[b] | $\text{FTY} = \frac{\text{output} - \text{rework}}{\text{input}} = e^{-\text{DPO}}$ | Output = defect-free units from the operation<br>Input = units entering the operation for processing<br>Rework = number of reprocessed units |
| (4) Rolled throughput yield (RTY; operations in series) | $\text{RTY} = \prod_{i=1}^{n} \text{FTY}_i$ | $\text{FTY}_i$ = first-time yield of the $i$th operation<br>$n$ = number of operations |
| (5) Sigma score ($Z$ score)[c] | $Z\,\text{score} = \frac{\lvert \text{SL} - \bar{x} \rvert}{\sigma}$ | SL = specification limit<br>$\bar{x}$ = process mean<br>$\sigma$ = process standard deviation |
| (6) Throughput yield (operations in parallel) | $\text{RTY} = \sum_{i=1}^{n} (Y_i \times p_i)$ | $Y_i$ = RTY at the $i$th operation<br>$n$ = number of parallel, interchangeable operations<br>$p_i$ = share of the $i$th operation on total |
| (7) On-time shipment (OT) | $\text{OT} = \frac{\text{OS}}{N}$ | OS = orders shipped complete and on or before due date<br>$N$ = total orders |

[a] Opportunities for a defect are determined with the customer’s needs in mind. For example, a prefinished door may have eight attributes that are critical for customer satisfaction (e.g., finishing, color, width, length, wood characteristics, smoothness, joint quality, and squareness). These attributes can be considered as opportunities for defects.

[b] For large samples and low defect rates, FTY can be approximated as $e^{-\text{DPO}}$.

[c] The $Z$ score for each SC component is calculated using the inverse normal distribution and looking for the value that corresponds with FTY [$Z$ score = $N^{-1}$(RTY)]. To consider shifts in the process over a long period, a long-term $Z$ score is calculated by adding 1.5 to the short-term $Z$ score. The overall SC $Z$ score is calculated by transforming RTY to DPO [DPO = −ln(RTY)] and then reading the corresponding value in a normal distribution table.

Table 2.—Defect definitions for supply chain time and product quality performance.

| Supply chain level | Quality attribute | Defect definition |
|---|---|---|
| Time performance | | |
| Lumber supplier | On-time delivery to next plant | Lumber load delivered after order due date |
| Components plant | On-time delivery to next plant | Order shipped to next facility after due date |
| Assembly plant | On-time delivery to retailer | Order shipped to next facility after due date |
| Retailer | On-time completion | Product delivered after order due date |
| Product quality | | |
| Lumber supplier | Quality conformance of lumber | Lumber load does not meet purchase order specs |
| Components plant | Component quality conformance | Nonconformance in one of *n* quality attributes |
| Assembly plant | Final product quality conformance | Nonconformance in one of *n* quality attributes |
| Retailer | Quality of construction and installation | Damage, installation errors, plant errors |
| Overall performance | | |
| Supply chain | Customer satisfaction | Satisfaction level less than 80% |

annualized improvement rate of 68 percent, or a monthly target of 9 percent improvement.

Note that in Figure 4a, the contribution of each SC entity to the overall quality performance can be clearly identified and compared with other entities on a similar scale. For example, the components plant is the major contributor to defect rate in the SC of study (3.29 sigma is equivalent to 37,674 defects per million opportunities); thus, any quality

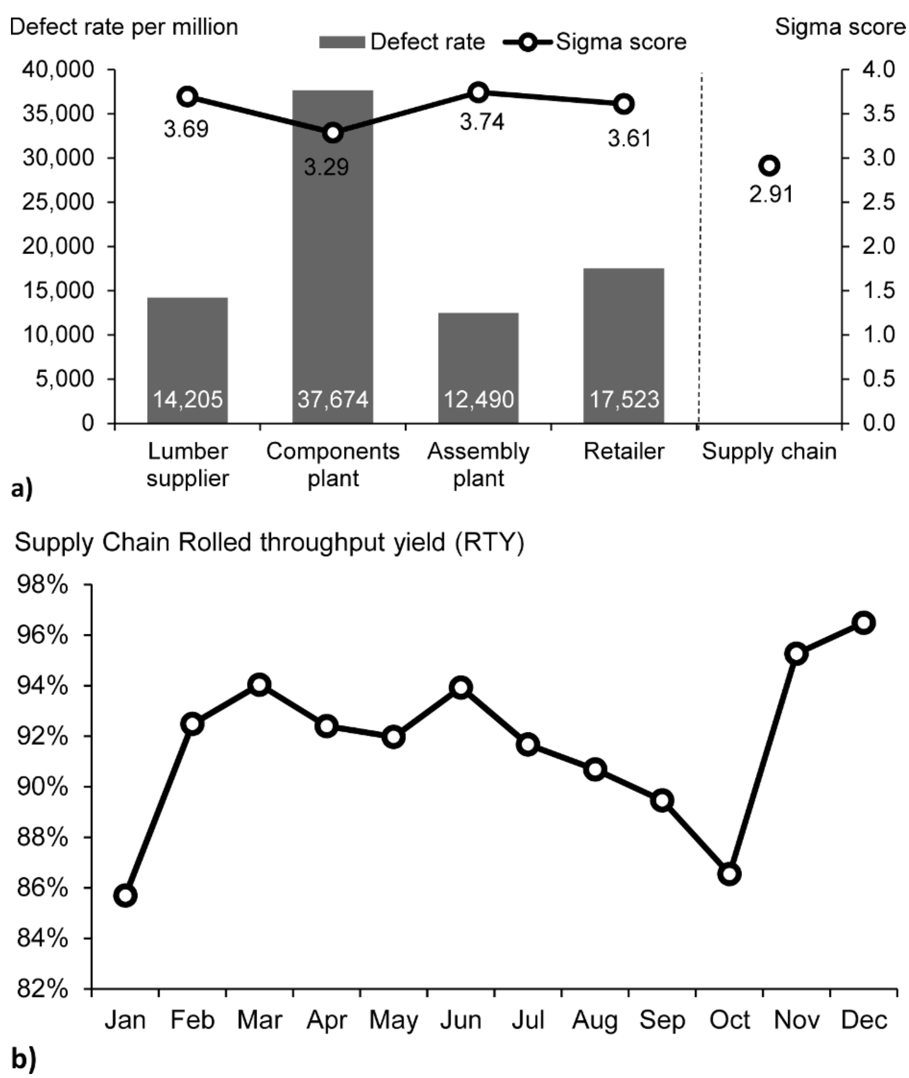


Figure 4.—Supply chain measures of performance: (a) defect rate and sigma score and (b) rolled throughput yield.

improvement initiative at the SC level should start there. The SC overall indicator is the RTY for all plants (Table 1, Eq. 4), calculated based on the yields at each SC component. This can be transformed to defects per opportunity and then to a sigma score, which is reported to the right in Figure 4a. Figure 4b shows monthly RTY over a 1-year period. RTY measures the probability that a product unit can pass defect-free through a number of consecutive processes. This information allows managers to compare performance at different times of the year and relate it to specific events or changes in demand. For example, in the case study, the lowest points in Figure 4b correspond with the months having the highest demand (January and October), suggesting that improvement in capacity planning could potentially result in better quality performance. Similar analysis for each SC member could reveal more specific information that would be useful when prioritizing improvement projects.

## Validation

A Monte Carlo simulation model was developed to validate the proposed performance measurement system by comparing its results with historical values. The structure of the simulation is illustrated in Figure 5. Past quality performance data were used to determine statistical distributions and random generation equations. The baseline case is based on a year's worth of actual performance data, and the model does not consider capital investments to increase capacity. Thus, it is only valid over a limited range of demand change. Statistical distribution and good-of-fitness tests can be found in Table 3.

Figure 6 shows the simulation output used to validate the model. In Figure 6a, the simulated value for the defect rate (expressed on a per-million basis) at every step in the SC is shown along with the historical value. It can be seen that the simulated value is within one standard deviation from the historical value, which was used as a measure of how well the model approximated historical behavior. The simulation also helps generate scenarios under different conditions to see how changes in important variables affect overall quality performance. Figure 6b shows the impact of changing demand (as a fraction of the baseline case) on the SC throughput yield. It can be observed that yield decreases by an average of 1 percent for every 25 percent increase in demand, because higher schedule pressure leads to more production errors (Oliva and Sterman 2001).

Other scenarios, like impact of changes in lumber grade mix on overall quality (Fig. 7), can be tested using the simulations. Management could benefit from this tool to generate information useful for decision making at both plant and SC levels.

## Summary

Results from a previous research study in a wood products SC revealed a need to develop SC measures of performance. To address this need, an SC performance measurement system for a wood products value stream was suggested. A set of measures for time performance and

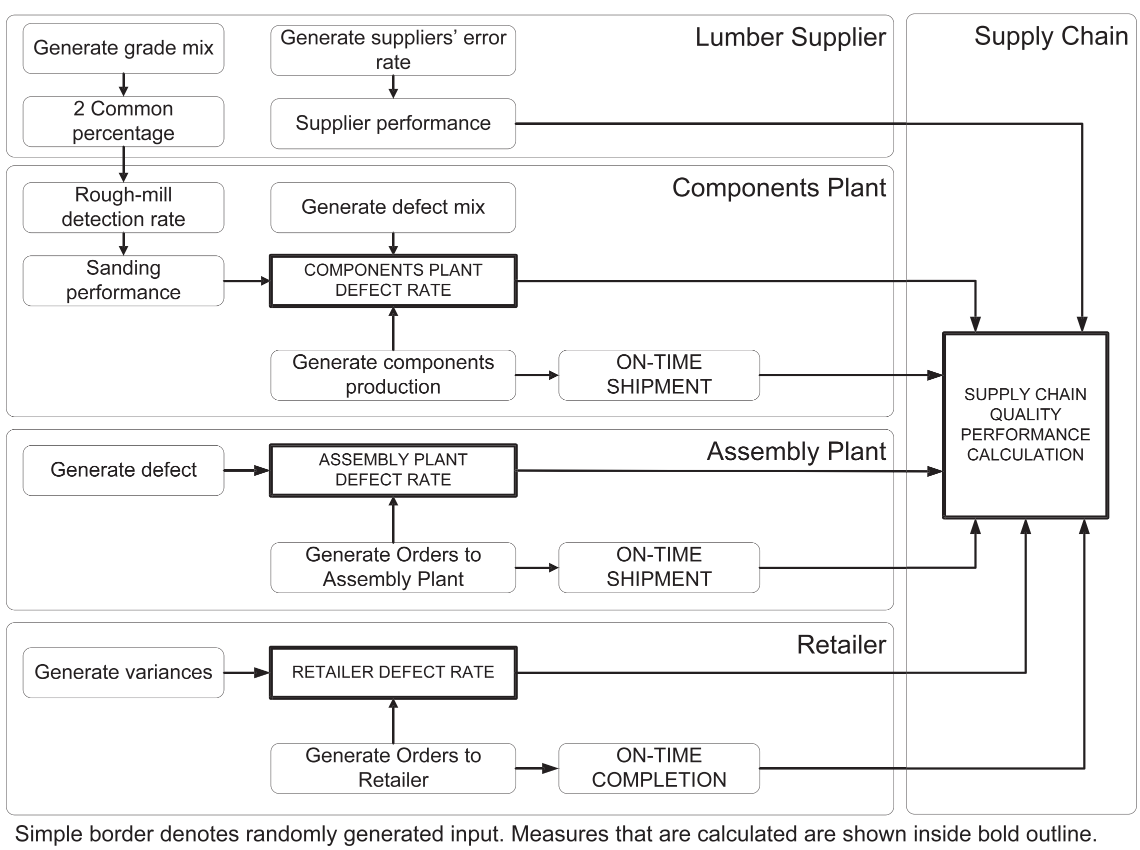


*Figure 5.—Monte Carlo simulation of quality performance structure.*

*Table 3.—Distribution fits and goodness-of-fit test for Monte Carlo simulation.*

| Category | Variable | $n$[a] | Random generation equation and parameters[b] | MSE/SD[c] | $P$ value[d] |
|---|---|---|---|---|---|
| Missed grade (supplier's error rate) | Misses supplier 3 | 110 | Poisson (0.03636) | 0.000 | <0.01 |
| | Misses supplier 4 | 164 | Poisson (0.08536) | 0.000 | <0.01 |
| | Misses supplier 5 | 110 | Poisson (0.00000) | 0.000 | <0.01 |
| Percentage of 2-Com lumber in mix | % 2C red oak | 14 | Gamma (0.00342,7.73) | 0.009 | >0.15 |
| | % 2C cherry | 14 | 0.04 + 0.1 × Beta (1.62,1.86) | 0.019 | >0.15 |
| | % 2C soft maple | 14 | 0.03 + Lognormal (0.0369, 0.0196) | 0.001 | >0.15 |
| Demand (order generator) | Components plant | 12 | Normal (0.0277;36,136) | 0.004 | >0.15 |
| | Assembly plant | 12 | Triangular (−1,870; −1,050;2,920) | 0.038 | >0.15 |
| | Retail | 12 | Triangular (−56;16.8;48) | 0.009 | >0.15 |
| On-time shipment performance | Components plant on-time | 17 | [1.01 − 8.4E−8×Production] + | NA | <0.01 |
| | | | [−0.01 + 0.02 × Beta (2.26,2.26)] | 0.020 | >0.15 |
| | Assembly plant on-time | 12 | [0.99 − 6.7E−7 × Orders] + | NA | =0.05 |
| | | | [−0.01 + 0.02 × Beta (10.9,10.9)] | 0.011 | >0.15 |
| | Retailer on time | 58 | [−5.60 + −0.14 × Orders] + | NA | =0.00 |
| | | | [−0.13 + 0.25 × Beta (3.46,3.06)] | 0.005 | >0.15 |
| Components plant quality performance | Final defect rate | 12 | [8,985 + 0.08 × Production] + | NA | =0.02 |
| | | | [Triangular (−8,090; −1,380;14,300)] | 0.085 | >0.15 |
| | Defect percentages | 1,538 | Poisson distribution for 11 defect categories | 0.000 | <0.01 |
| Assembly plant performance (defect rate) | Final defect rate | 12 | −5,290 + 9.47 × Orders | NA | =0.01 |
| | Eyes-of-the-customer | 12 | [0.95 − 1.2E−6 × Orders] + | NA | =0.03 |
| | | | [−0.01 + 0.02 × Beta (4.75,4.75)] | 0.023 | >0.15 |
| | Defect percentages | 3,000 | Poisson for 10 defect categories | 0.000 | <0.01 |
| | Backorders | 12 | | NA | =0.04 |
| Retailer performance (variances) | Product quality | 12 | Product quality component | NA | NA |
| | Defect percentages | 58 | Poisson for 10 defect categories | 0.000 | <0.01 |

[a] $n$ = number of raw data points.
[b] Parameters calculated with Input Analyzer by Rockwell Software.
[c] Mean square error of fitted distribution and actual data/standard deviation. NA = not applicable.
[d] $P$ value: (1) Kolmogorov-Smirnov goodness-of-fit test (high values denote a good fit) for continuous distributions, (2) chi-square test for discrete distributions (low values denote a good fit), and (3) significance of linear regression where appropriate.

product quality were developed and then validated with historical data.

Companies can benefit from using the process described here by developing a performance measurement system that helps them to align strategies and activities in the value stream. Such a system also encourages cooperation between SC partners by improving transparency and providing a common language, and it facilitates differentiation between SCs. A performance measurement system can contribute to the competitive advantage of the firm and the SC.

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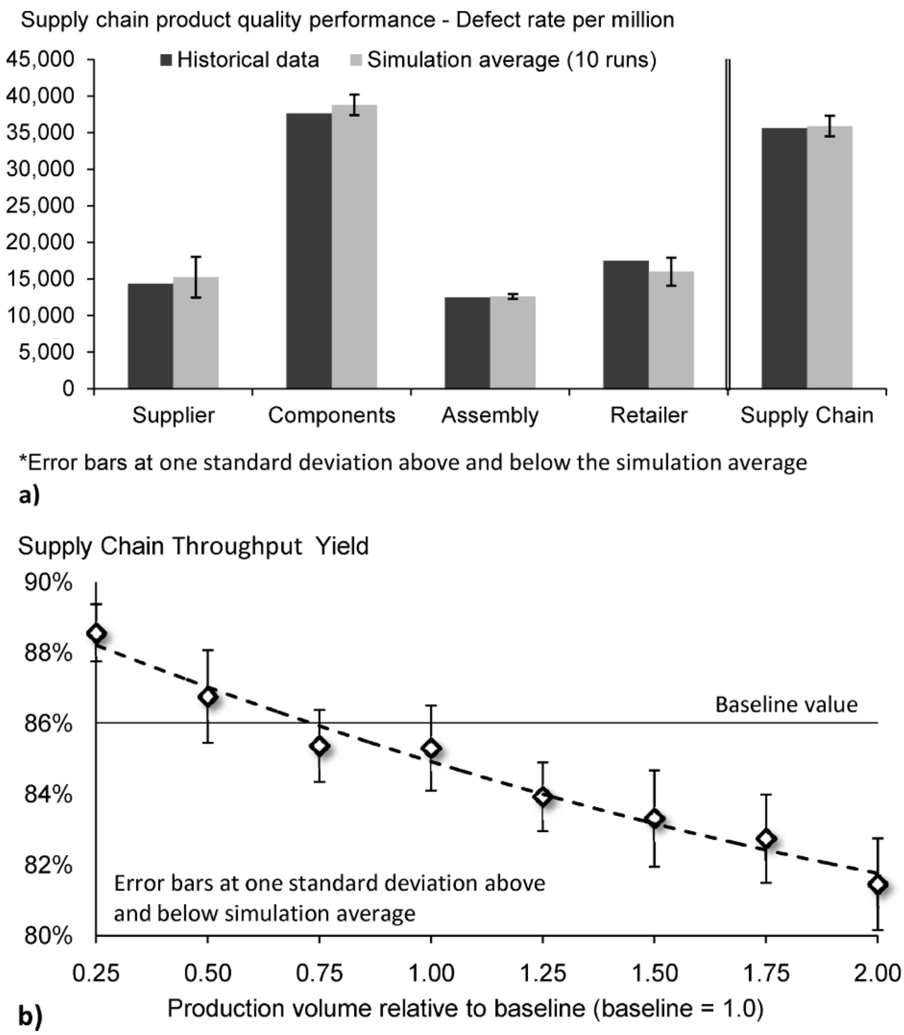


*Figure 6.—Simulation output: (a) supply chain defect rate and (b) impact of demand on supply chain performance.*

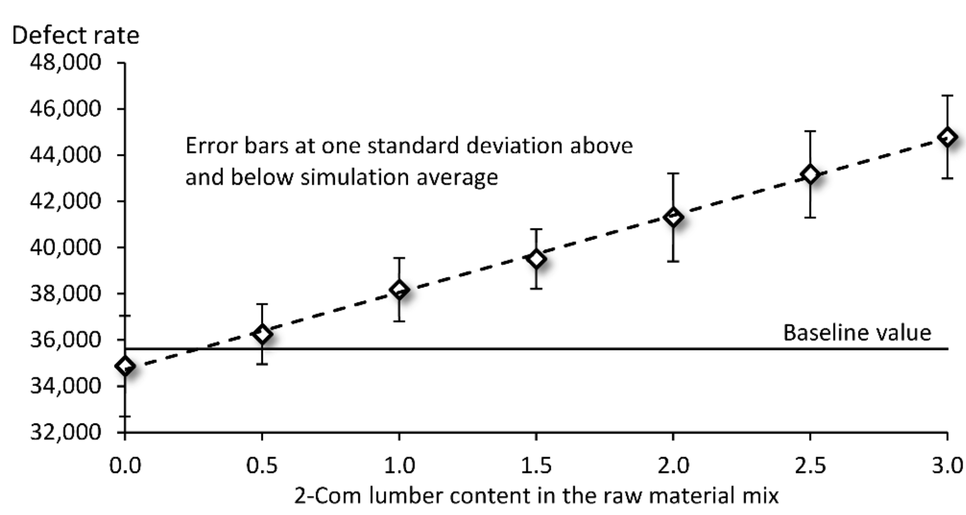


*Figure 7.—Simulation output: impact of changes in lumber grade mix on quality performance.*

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