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► **To cite this version:**

Rodrigo Reyes Levalle, Manuel Scavarda, Hyesung Seok, Shimon Y. Nof. PROTOCOLS FOR SUSTAINABLE COLLABORATION IN SUPPLY NETWORKS. 9th International Conference on Modeling, Optimization & SIMulation, Jun 2012, Bordeaux, France. hal-00728638

**HAL Id: hal-00728638**

**<https://hal.science/hal-00728638>**

Submitted on 30 Aug 2012

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# PROTOCOLS FOR SUSTAINABLE COLLABORATION IN SUPPLY NETWORKS

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**ABSTRACT:** Industries with automated discrete production lines struggle with intrinsic process variability affected, among other factors, by the rules that coordinate interactions among machines. Similarly, increasing complexity to coordinate supply networks affects delivery performance, inventory levels across the network, and production facilities' capacity leading to frequent product flow disruptions. Rules and protocols to enable coordination among the different parts of both production lines and supply networks are necessary to ensure long term stability and sustainability. A Collaborative Control Theory approach based on three of its principles is developed to the production line control problem, and a protocol for supply networks is proposed. A case study shows that Collaborative Production Line Control (CPLC) outperform traditional models, achieving a 43% reduction in throughput variability, 24% reduction in WIP, and a 0.5% increase in service level.

**KEYWORDS:** Collaborative Control Theory, Supply Networks, Sustainability, Supply Chain.

## 1. INTRODUCTION

Since the development of the assembly line in the early 1900's, industry has sought ways to improve production lines' performance to deliver more products, with lower lead time and better quality. Performance improvement, which started as a cost-reduction effort in manufacturing facilities, was soon transformed into a quest for better customer service, which pushed supply networks to grow in complexity in order to increase customer reachability, while reducing delivery time. However, as supply networks became more complex, delivery performance, inventory levels, and production facilities' capacity started to become affected by the difficulties arising from coordinating the network, leading to frequent product flow disruptions. It became evident that rules and protocols to enable coordination among the different parts of the supply network were necessary to ensure long term stability and sustainability of the network.

As defined by Elkington, 1998, sustainability consists of three balanced criteria, including environmental, social and economic sustainability, which combined are referred to as “triple bottom line” (Figure 1). For a vast majority of authors researching on sustainability, sustainable development involves the simultaneous pursuit of economic prosperity, environmental quality, and social equity (WBCSD, 2011). Economic sustainability has become a central issue in many industries, especially those producing commodity products, where companies compete on price and customer service. From the manufacturing perspective,

economic sustainability through higher profit margins has been pursued in the early years by seeking economies of scale. As a result, many production lines acquired the capability of producing a high volume of products in short periods of time, making discrete production lines more similar to continuous processes, where automation plays a key role. As demand for commodity products became asymptotic, marginal gains obtained by investing in state-of-the-art manufacturing equipment banished and a new era of improvement by reducing waste began. To achieve higher performance in production lines it became necessary to standardize operating procedures, attain greater coordination among automated, high-volume processes, and develop and implement optimal buffer management techniques.

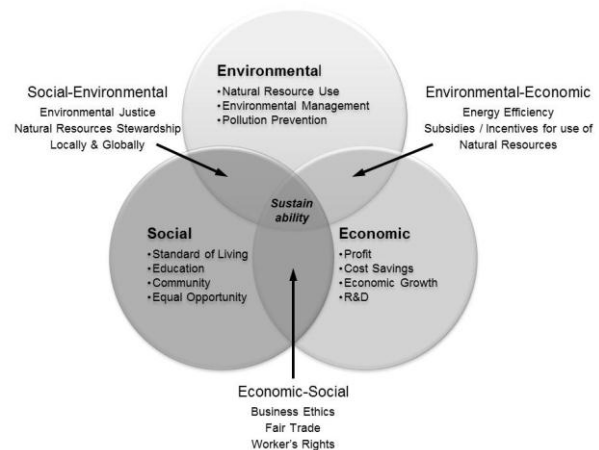


Figure 1. Three pillars of sustainability, adapted from Sustainability, 2002.

From the supply network perspective, growth has been influenced by both, economic and environmental sustainability. Regarding the demand side, increasing customer pressure for lower delivery times, and the development of new geographically spread markets, has forced supply networks to grow in size, as well as in complexity. Large mature markets could be easily supplied with a set distribution centers strategically located across the geography of interest, but as new markets require products, cross-docking facilities and wholesalers come into play to ensure adequate product capillarity. Moreover, outsourcing of non-core activities (such as distribution), and 3PL or 4PL practices, further increase the networks' complexity. Environmental sustainability concerns arise from the use of scarce natural resources to make products. The need for new "green" suppliers to deliver raw materials while minimizing sourcing risk contributed to the complexity increase in the supply side of the network.

The problem of improving customer service involves achieving higher performance and flexibility, by reducing process variability in production facilities, and enhancing collaboration strategies across the supply network. Several models for buffer management and production control can be found in industrial engineering literature but most are applicable only to assembly lines with low production rates or high stability. In most cases, high volume production lines that have not reached stability face a dearth of methodologies to deal with intrinsic process variability, especially in real time. Many researchers have proposed collaboration strategies and protocols for supply networks, but they lack integration with production line performance optimization.

## 2. LITERATURE REVIEW

### 2.1 Traditional, and Collaborative Control Theory approach to production line control

Many researchers have studied the problem of production line control under uncertain machine behavior and proposed different methodologies to increase throughput while minimizing WIP. Traditional control policies range from simple buffer management, e.g. base-stock policy, to complex dynamic buffer control policies, such as DWIP (Yang *et al.*, 2006). Table 1 shows a classification of traditional methods used for production line control, based on four factors; buffer management, production rates management, real-time decision making, and system-state evolution forecast. A more detailed analysis of the methods can be found in Reyes Levalle *et al.*, 2012.

Buffer management methods focus their control over the production line on a single variable, WIP levels. Alternative methods for line control based on two or more variables have been developed, relying on certain level of collaboration between processes to overcome

unexpected downtimes, maintaining throughput while simultaneously reducing the required level of WIP. Collaborative Control Theory, CCT, introduced by Nof, 2003 and 2007, comprises six design principles which provide a common analysis framework to enable the control of the collaboration level of different systems. A review of collaborative methods, shown in Table 1 can be found in Reyes Levalle *et al.*, 2012.

		Factor			
		Buffer management	Production rates mgmt	Real-time decision making	System state evolution forecast
Traditional	Base stock	Fixed WIP level (allocated to each buffer)	No	Job release (pulled by downstream buffer)	No
	Kanban	Limited maximum WIP	No	Job release (pulled demand)	No
	CONWIP	Fixed WIP level (unallocated)	No	Job release (based on WIP target)	No
	DWIP	Fixed WIP level (unallocated)	No	Job release (based on dynamically updated WIP target)	No
	Learning Agents	WIP level constrained within a range (unallocated)	No	Job release (based on system status)	No
Collaborative	Optimal controller selection	No buffer mgmt (only capacity constraints)	Yes	Production rates are set dynamically based on system status and controller library	No
	SRDM	Depends on the policy	Depends on the policy	Depends on the policy	No, but is considered in simulation results

Table 1: Traditional, and collaborative control methodologies summary, Reyes Levalle *et al.*, 2012.

### 2.2 Collaboration models for supply networks

Several models to enable collaboration among the components of a supply network have been proposed in recent years, to address parallel task execution, production and distribution planning, resource allocation and re-allocation, and network flow disruption mitigation, among other problems.

Among the most widespread collaboration models in industry are Collaborative Planning, Forecasting, and Replenishment, CPFR, introduced by the Voluntary Interindustry Commerce Standards, and Vendor Managed Inventory, VMI. CPFR provides a framework to enable collaboration and information sharing among components of a supply network to deliver higher service level while minimizing flow disruptions and WIP throughout the supply network. However, no protocol or tool is proposed for making collaborative decisions. Vendor Managed Inventory is a strategy related solely to inventory management, and although it allows for some degree of collaboration among suppliers and customers, optimization is local and static. An application algorithm for a four-stage supply chain can be found in Darwish, and Odah, 2010; an analysis of the requirements to implement VMI can be found in Danese, 2006. Sari, 2008, compared VMI and CPFR and concluded that CPFR "produces lower total supply chain cost as well as

higher customer service levels”. Moreover, CPFRR shows lower sensitivity to demand uncertainty when compared to VMI. However, under short lead times or high capacity utilization, the difference in benefits between CPFRR and VMI is reduced.

Ceroni and Nof, 2002, introduced a Distributed Parallel Integration Evaluation Model (DPIEM), which provides a protocol for optimizing the integrated operation of distributed organizations. In order to achieve its goals, each distributed organization must perform a series of tasks, some of which are also present in the workflow of a different distributed organization. Then, collaboration among several organizations with shared tasks, can improve resource efficiency and reduce total process time. However, parallelism can also increase server costs and the trade-off between these and gains from higher efficiency and shorter process time must be optimized. DPIEM does not address collaboration of resources within a supply network to achieve its goal.

Gonheim and Bentahar, 2008, developed an adaptive reconfiguration strategy for a Reconfigurable Virtual Supply Network (RVSN) to respond to market changes by altering its organization structure. A RVSN was defined by Lin *et al.*, 1995, as a “rapidly configured multi-disciplinary network of small, process-specific firms configured to meet a window of opportunity to design and produce a specific product”. The strategy developed by Gonheim and Bentahar, 2008, is based on a multi-agent system, where agents representing different components of the network bid to be awarded tasks. Each agent negotiates with another agent until criteria for both agents’ objectives are met and a contract is agreed. Although not proven, the strategy introduces the concept of adaptive reconfiguration, in which a supply network can alter its configuration based on market conditions to improve customer service.

Jung and Jeong, 2005, proposed a Decentralized Production-Distribution Planning System (DPDPS) to integrate production and distribution plans within a supply network into a global, coordinated, production-distribution plan to satisfy the customer demand with minimum costs. Typically, each unit will aim to minimize its own cost, and the conflict would be solved by a centralized decision maker with authority to balance the cost trade-off. However, due to the complex nature of current supply networks, no centralized decision is possible; therefore the need for a decentralized approach. DPDPS is an agent based model in which negotiations between the functions produce a feasible solution (considering constraints of both functions), and achieve the lowest overall cost. In contrast to DPIEM, the system introduced by Jung and Jeong, 2005, focuses on the internal optimization of tasks by enabling collaboration among different functions within a supply network.

Craighead *et al.*, 2007, defined two disruption mitigation capabilities to anticipate and overcome product flow

interruptions in supply networks. The first capability, recovery capability, is defined as the interaction among supply network components to coordinate resources to overcome partial or complete interruption of product flow. The second mitigation capability, warning capability, is defined as the capacity of the supply network components to detect possible flow interruptions, and coordinate and implement the necessary actions to minimize impact on product flow. According to Shao and Pan, 2009, these disruption mitigation capabilities are one of the necessary components for supply networks collaboration. Rodriguez *et al.*, 2007, addressed the problem of detecting possible interruptions in the supply network, making real time adjustment of supply, production, and distribution plans, and re-allocating manufacturing and distribution resources. The Sense-and-Response System (SRS) proposed by the authors consists of a series of “e-sensors” located in the interface of two functions, such as suppliers and production, that can detect deviations from pre-defined ranges for key indicators. The “e-sensors” are computer programs that monitor the supply network by continuously scanning information databases, perform analysis of deviations, and suggest a course of action (plan adjustment and resource re-allocation) to human decision makers (or “e-collaborators”) who are accountable for the interaction between the two functions sensed. SRS capabilities can build on those of DPIEM and/or DPDPS, enabling early conflict detection and prevention within the collaborative supply network to adjust interaction among the organizations that compose the network. This will in turn increase the supply network capability of delivering high customer service.

The contribution of each methodology to enable supply network collaboration is summarized in Table 2.

Relevance to Supply Network (SN) collaboration		
SN Collaboration Methodology	CPFRR	<ul style="list-style-type: none"> <li>Guidelines for collaboration among suppliers and customers</li> </ul>
	DPIEM	<ul style="list-style-type: none"> <li>Model for optimization of the integrated operation of distributed organizations</li> </ul>
	Adaptive Reconfiguration Strategy	<ul style="list-style-type: none"> <li>Supply networks are reconfigured over time</li> <li>Multi-agent system enables negotiation and collaboration of different components of the network to fulfill local and global objectives</li> </ul>
	DPDPS	<ul style="list-style-type: none"> <li>Decentralized agent based model in which negotiations between different supply network functions produce a feasible solution with minimum overall cost</li> <li>System constraints are considered in the agents negotiation</li> </ul>
	Sense-and-Response System	<ul style="list-style-type: none"> <li>e-sensors located in the interface of two functions enable predictive capabilities to anticipate product flow disruptions</li> <li>e-collaborators (humans) make decisions based on the system’s suggestion for plan adjustment and resource re-allocation</li> </ul>

Table 2: Methodologies for supply network collaboration

Evidence from the reviewed papers regarding the potential benefits of developing a collaboration protocol for supply networks, based on the principles of Collaborative Control Theory, is clear. Therefore, the objective of this research paper is to introduce a collaboration protocol for supply networks, based on CCT principles. The study is organized as follows: In the

methodology section a mathematical definition of the problem is presented. Second, the CCT based solution methodology for production line control is introduced, and a generalization to supply networks is developed. Third, an experimental comparison of the proposed production line control methodology and other solution approaches is made to evaluate its performance. Finally, conclusions from the results obtained and future work directions are presented.

### 3. METHODOLOGY

#### 3.1 Standardized mathematical model for production lines

Production lines can be highly different across industries; moreover, they may be dissimilar within the same industry when considering different technologies, or diverse machine arrangements and layouts. However, all production lines share features that can be treated as equal in order to model their behavior using a common mathematical model. To do so, it is necessary to divide the production line into its elemental components, processes, and buffers which describe the two main activities through which raw materials and WIP can flow: transformations, and storage.

##### 3.1.1 The building blocks: Process and buffer models

A process is any activity on materials that adds value and, in general terms, has physical and logical inputs and outputs. Physical I/O are related to material flow, i.e., raw materials and items produced. A set of functions relates physical inputs to outputs, e.g., rate of production. Logical I/O comprises the variables and parameters required by the process control logic and the state variables that describe the process at any given point in time.

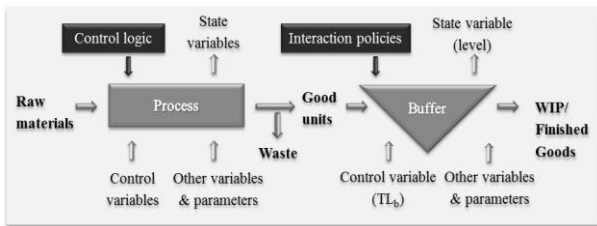


Figure 2: Production and buffer model

Buffers, defined as storage systems or areas that follow a given process (Figure 2) have two main purposes: store the finished parts of the preceding process, and smooth system throughput. Buffer levels,  $L_b$ , are controlled by line or process interaction policies whose goal is to achieve and hold a target level,  $TL_b$ .

##### 3.1.2 Constructing a production line model

Process/buffer pairs can be arranged in combinations to form a line. Several lines can be set in parallel and connected prior to or after an assembly operation or a common storage area. An interaction point is a physical location where two or more lines connect. Interaction

points have bill of materials constraints and a control policy to decide which of the exiting lines is served, when more than one exist.

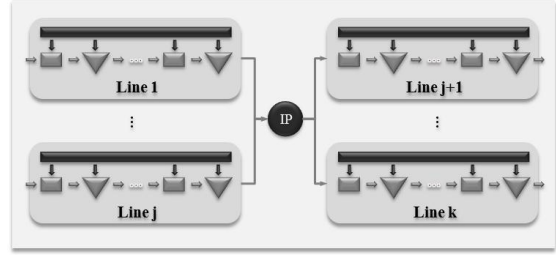


Figure 3: Production lines and interaction (IP)

##### 3.1.3 Enabling interaction between the building blocks: Production line control

At any given point in time  $t$ , the production line can be characterized by the status of the processes and the status of the buffers. In a network with  $n$  processes, there will be  $2n$  system state variables  $s_k^t$  characterizing the system at any point in time  $t$ . Let  $s_{2p-1}^t$  define process  $p$  according to

$$s_{2p-1}^t = \begin{cases} 1, & p \text{ is ok} \\ 0, & p \text{ is failed} \end{cases} \quad p = 1, 2, \dots, n \quad (1)$$

Correspondingly, let  $s_{2b}^t$  define buffer  $b$  according to

$$s_{2b}^t = \begin{cases} 1, & |L_b - TL_b| \leq \delta_b \\ 0, & |L_b - TL_b| > \delta_b \end{cases} \quad b = 1, 2, \dots, n \quad (2)$$

where  $\delta_b$  is the tolerance for  $TL_b$  deviation.

Let  $S^t$  be a vector of  $2n$  components such that  $S^t = (s_1^t, \dots, s_{2n}^t)$  then the system state at time  $t$  is fully described by  $S^t$ . Since all  $s_k^t$  are binary, the number of possible system states at a given time  $t$  is  $2^{2n}$ , therefore the number of states grows exponentially with increasing system complexity.

The interactions among the lines that constitute the network and among processes that compose each of the lines are regulated by control policies  $CP_i$ . When changes in system state occur, different  $CP_i$  may be enforced to regulate the system's performance. Let  $\theta$  be the set of  $CP_i^t$  applied on the system, where  $t$  is the instant of enforcement for control policy  $i$ , then  $\theta$  is defined as the control strategy for the production line. If a production line is run for a given period of time where state changes occur and their durations  $\Delta t^{t_j}$  are known a priori, the best control strategy can be calculated based on the available information.

$$\text{Optimal } \theta = \{\text{Optimal } CP^{t_0}; \dots; \text{Optimal } CP^{t_j}\}, \quad (3)$$

$$\text{where } \text{Optimal } CP^{t_m} = f(S^{t_m}, \Delta t^{t_m}, \dots, S^{t_j}, \Delta t^{t_j})$$

However, due to the stochastic nature of the system, information on state changes is unknown a priori.

### 3.2 Extension of the production lines' mathematical model to supply networks

As with production lines, supply networks can be highly different across industries. For instance, manufacturing and distributing steel rolls requires a rather simple supply network since a small number of raw materials are required and demand is highly concentrated in large customers. Conversely, manufacturing and distributing a laptop computer involves an intricate network, where raw materials are supplied from different parts of the world to one or more assembly facilities, to then be distributed to a highly atomized demand. Regardless of the network complexity, the steps involved in transforming raw materials into finished products delivered to the final customer can be comprised in three activities: transformation, storage, and transportation.

Transformations occur in production facilities, where raw materials are converted into WIP or finished goods. This process involves logical I/O that feed the facility's control policy which comprises production scheduling, dispatching rules, and production line control. Then, the model proposed for processes in section 3.1.1 can be utilized to model production facilities.

Transportation is a special process where physical inputs are not altered; no transformation is performed. However, WIP or finished products are moved between buffers, and this activity implies a period unavailability for further processing or storage. This is analogous to what occurs in a production process, where products are unavailable while undergoing physical transformations. Therefore, modeling of transportation activities is possible using the model proposed for processes in section 3.1.1. As for control policies, in the case of transportation, these regulate vehicle scheduling and dispatch, truck load consolidation, and delivery routing.

In supply networks, storage activities occur in distribution centers and cross-docking facilities. The dynamics of these is similar to that of a production buffer; therefore the model proposed in section 3.1.1 is applicable to supply network storage activities. Interaction points connect the different components of the network, and can regulate raw material, WIP, and finished goods flow. Building blocks can be sequentially connected to model a supply network, and as in the case of production lines, processes are followed by buffers. A major difference between production lines and supply networks must be made in terms of control policies governing the interaction of the different components. In production lines, a centralized control system, which has decision authority over all components, is responsible for enabling collaboration to maximize performance. In supply networks, components may belong to different organizations making centralized control only feasible within a given organization. Between organizations, a decentralized control methodology is required to enable collaboration. In such context, each component tries to

achieve its own objectives, as well as the global objectives of the supply network.

### 3.3 Collaborative Production Line Control (CPLC)

To explore the benefits of enabling collaborative resolution for the problem of production line control, a control methodology named Collaborative Production Line Control (CPLC) was designed based on three principles of Collaborative Control Theory.

- (1) Cooperation Requirements Planning (CRP)
- (2) Conflict and Error Detection and Prognostics (CEDP)
- (3) Fault-Tolerance by Teaming (FTT)

An extensive description of the principles comprising CCT can be found in Nof, 2007, and Velasquez and Nof, 2009. However, in order to fully explain the design of CPLC we will briefly introduce each of the three above principles.

The first principle, CRP, involves two phases, namely CRP-I and CRP-II. CRP-I consists of planning resource allocation to tasks and defining task execution procedures and sequence; considering the system's objectives and constraints, to enable collaboration among resources. In the case of a production line, machines are the collaborative resources which have a double-fold goal of keeping low WIP inventory while maximizing throughput. This is valid regardless of the system status and therefore, machines must collaborate to overcome in the best possible manner the problems that occur during a production run. CRP-II consists of making real time adjustments to what has been defined in CRP-I, based on the current system status. This task is usually performed by job floor leaders who decide on what to do next using the available real time data and their best estimation of the future system behavior.

The second principle, CEDP, consists of building the capabilities that will allow the collaborative agents to anticipate any conflict arising in the near future, thus reducing the cost of resolving the imminent conflict. In the case of CPLC, this principle is embedded in a conflict forecasting tool and conflict prevention methodology that enables machines (the collaborating agents) to take actions to minimize the impact of such conflict on the lines' performance.

Finally, the third principle, fault tolerance by teaming, implies that with the right protocols, a set of collaborative agents, that are more prone to failure, can outperform a single flawless agent. Then, collaboration among these agents makes the system more robust and tolerant to failure of any one of the agents. The conflict prevention methodology provides the rules for machines to "help each other" overcome failures, thus making the production line more stable.

CPLC starts with the CRP-I step by defining the best static control policy (production rates  $R_p$  and target buffer levels  $L_b$ ) for every possible combination of process states  $s_{2p-1}^t, p = 1, 2, \dots, n$ , assuming that this condition is the steady state. To illustrate this process, consider the example production line of Figure 4.

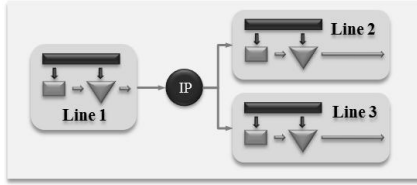


Figure 4: Example production line.

Taking into account only processes, there are eight different states, i.e., all process working (steady state), one process failed (three states, one for each line), two processes failed (three states) and all processes failed.

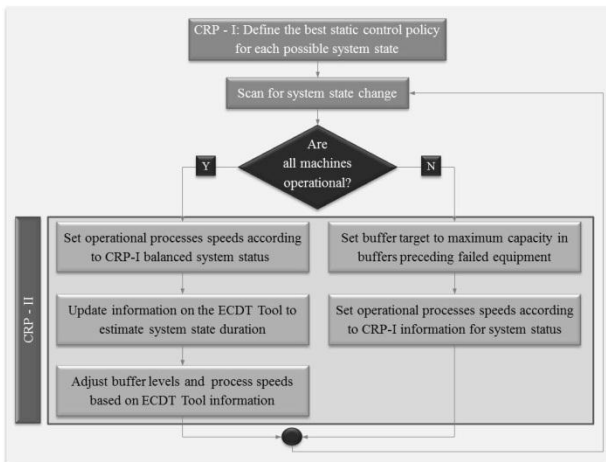


Figure 5: Collaborative Production Line Control (CPLC) Algorithm.

The CRP-I step involves determining the bottleneck in each state, setting all non-bottleneck process speeds according to the bottleneck capacity to cooperate in maximizing throughput, and all buffers targets to low values, ideally zero. The results obtained are stored in a database to be retrieved by the algorithm of the second phase, CRP-II.

CRP-II takes place during the execution of the balanced line configuration defined in CRP-I. It consists of making adjustments to the line configuration plan based on the system evolution. To adjust the control variables, information is gathered from the system (current status  $S^t$ ), the CRP-I database and an early conflict detection tool (ECDT). The principle of CEDP is applied to create the ECDT which feeds from historical machine time between failures and provides an estimate for the probability of each machine to be the next to fail based on the time of the last known failure event. This tool enables the decision making algorithm to anticipate the next system state change when running under balanced conditions, therefore enabling conflict prevention. Using

the CRP-I database information for the system status as a starting point, production rates  $R_p$  and target buffer levels  $L_b$  are adjusted. Adjustments consider current system information and ECDT information to provide a better system condition in the near future to deal with the next expected machine failure. In this way, machines collaborate to provide the next expected-to-fail machine a better condition to face the likely failure. To illustrate how this information is used in CRP-II, consider the system of Figure 4 operating in steady state and information from the ECDT indicating a high probability of process failure on line 3. Information from the CRP-I database shows that under this failure condition, throughput will be reduced. As a result, the algorithm increases speed in line 2 process. This has a dual objective: to reduce the level in line 1 buffer in order to prevent bottleneck idling, and to maintain system throughput as long as possible after the failure occurs.

### 3.4 Collaborative Supply Network Control

A collaborative supply network (CSN) is composed of several stages, each of which contains a set of network components connected to preceding and succeeding stages through interaction points (Figure 6) Network components of a CSN may belong to different organizations, each of which has a central control policy over its components. In this way, each organization can be optimized according to the CPLC principles. First, optimal control policies, for each possible network state in a given organization, are calculated during the CRP-I phase. Production schedules, distribution schedules, and inventory target levels in each storage facility are defined in this phase.

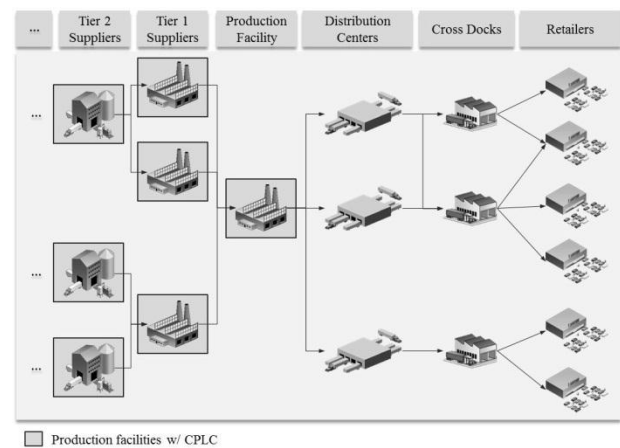


Figure 6: Collaborative Supply Network (CSN)

To define the balanced network configuration, corresponding balanced configurations from each organization are retrieved and a negotiation process takes place between interfaces of different organizations to define flow across the network. The negotiation process takes place under Collaborative Control Theory's fifth principle, Join/Leave/Remain, which addresses the identification of conditions and timing for individual organizations to join, leave, or remain in a



collaborative networked organization, CNO (Chituc and Nof, 2005, Yoon and Nof, 2010, Yoon *et al.*, 2011).

In the negotiation process, each party considers its own objectives and the overall network objectives. A series of measures that should be considered when a given organization analyzes the benefits of joining, leaving or remaining in a network with another organization are proposed in Scavarda and Nof, 2011, Scavarda, 2012, and Scavarda *et al.*, 2012. Among these measures are Organizational Activation Costs (total costs required to obtain flow through a previously inactive organization), Delta Operational Costs (total changes in costs within the organization), and Delta Coordination Costs (variation in the cost of coordinating operations with other organizations).

Through this process, CRP-I will consider alternative ways to convey products from the first supplier in tier n to the retailers in the opposite side of the supply chain, under different flow interruption situations. The optimal supply flow in each case should be defined based on the total cost of producing and moving all the required materials through the different chosen points of the supply chain in order to deliver products to the retailers, and the total leadtime.

A similar approach is used by Seok *et al.*, 2012, who propose a Sustainability - Decision Support Protocol (S-DSP) which consists of three sub-protocols; Disruption Analysis (DA), Negotiation Management (NM) and Knowledge Management (KM). (Figure 7)

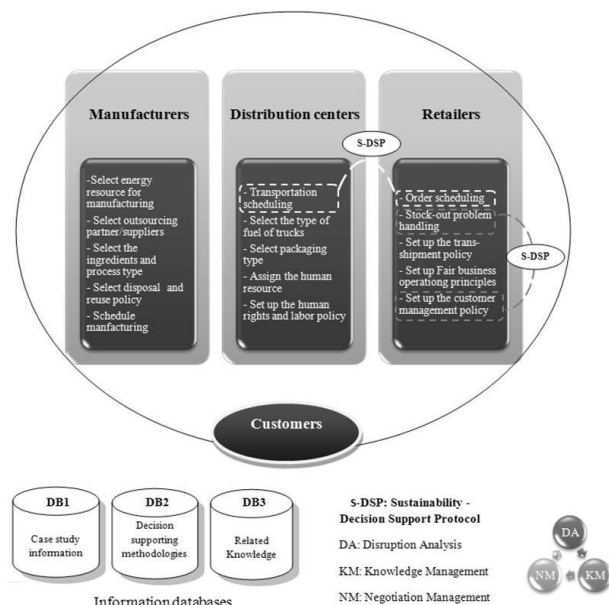


Figure 7: Sustainability - Decision Support Protocol (S-DSP), Seok *et al.*, 2012

Starting from a balanced network configuration, e-sensors, proposed by Rodriguez *et al.*, 2007, monitor the network state to detect changes. Whenever a state change occurs, the CRP-II phase begins. First, the

affected organization (the one where the state change occurred), defines its own best configuration in the new state. Then, this organization must negotiate with its interfacing organizations in order to define new flow across the network. Adjustments to production schedules, distribution schedules, and inventory target levels within each organization take place during the negotiation process, until a final solution is found.

In addition to detecting state changes, e-sensors can also identify trends in the network evolution, which may lead to future flow disruptions. In order to define the benefit of taking preventive actions, the cost of such measures is compared to the cost of the forecasted scenario with no intervention.

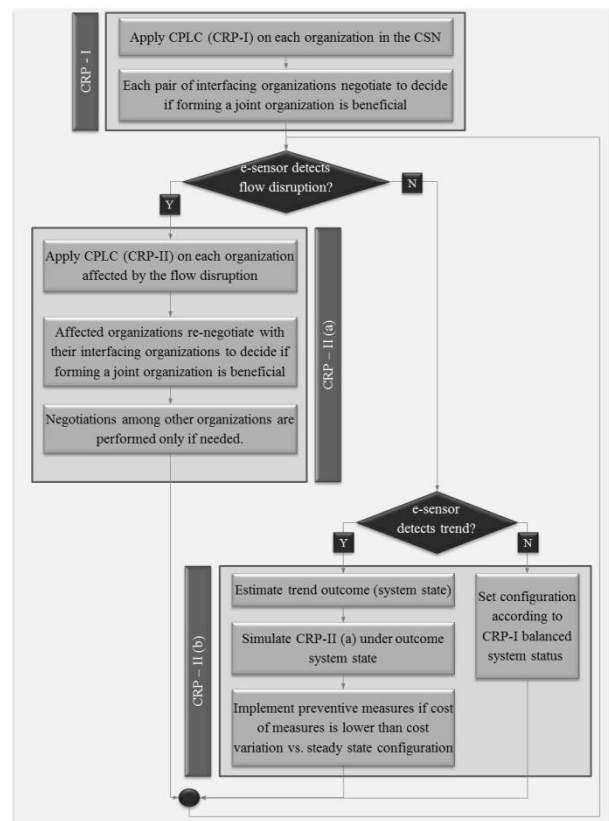


Figure 8: Collaborative Supply Network Control (CSNC) Algorithm.

#### 4. EXPERIMENTAL RESULTS

A tissue converting line was modeled in ARENA to test the feasibility of CPLC and compare its performance to other known control methods. High volume automated production systems such as the one in Figure 9 are often challenged by the succession of machine failures that lead to line downtimes and reduction of throughput. Whenever a machine is failed, WIP inventory builds up and eventually another machine stops due to lack of buffer space. This type of negative interaction between processes can be amplified if the integration policies and control logic parameters are not dynamically updated based on current and predicted system status.



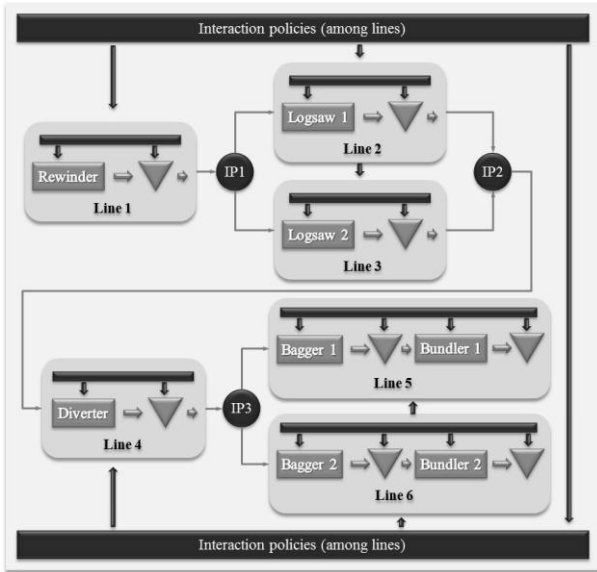


Figure 9: Tissue converting line model.

A list of the most relevant interaction policies indicating equipment involved, trigger conditions, actions and policy enforcement (automatic: controlled by plc's , or manual: controlled by the operator) is shown in Table 3.

	Manual or Auto	Equipment involved	Trigger condition/s	Action/s
Rewinder stop w/ full accumulator	Automatic	Rewinder Accumulator	Accumulator is full	Stop rewinder
Rewinder re-start	Automatic	Rewinder Accumulator	Accumulator below restart level after stop	Enable rewinder for operation
Log production	Automatic	Rewinder Accumulator	Rewinder not failed Accumulator not full	Produce 1 log
Rewinder speed control	Automatic / Manual	Rewinder Accumulator	Accumulator level out of target range	Adjust speed up or down
Accumulator discharge	Automatic	Accumulator Logsaw	Accumulator not empty Logsaw cradle is not full	Discharge 1 log
Roll production	Automatic	Logsaw Logsaw buffer	Logsaw not failed Logsaw buffer not full	Cut 1 roll
Logsaw speed control	Automatic / Manual	Accumulator Logsaw Logsaw buffer	Accumulator level out of target range	Adjust speed up or down
Diverter load/unload sequence	Automatic	Logsaw buffer Diverter Diverter buffer	Diverter buffer not full Logsaw buffer not empty Diverter not failed	Deliver 1 diverter load
Bagger/Diverter failure interaction	Automatic	Bagger Diverter	Bagger failed	Block deliveries to failed bagger
Pack production	Automatic	Bagger Diverter buffer Bagger buffer	Bagger not failed Diverter buffer not empty Bagger buffer not full	Produce 1 pack
Bagger speed control	Automatic / Manual	Bagger Diverter buffer Bagger buffer	Diverter buffer level out of target range	Adjust speed up or down
Bagger/Bundler failure interaction	Automatic	Bagger Bundler	Bundler failed	Stop bagger feeding failed bundler
Bundle production	Automatic / Manual	Bundler Bundler buffer	Bundler not failed Bagger buffer not empty	Produce 1 bundle

Table 3: Main interaction policies summary.

A week of production was simulated after one day of warm up. Each simulation run was replicated 100 times. The results are shown in Table 4 and Figure 10.

Control Policy	Service Level (%)	Throughput			WIP (cs)
		Avg. (cs/min)	Std. Dev. (cs/min)	Std. Dev. (% of Avg.)	
Base stock	99.390	7.2555	0.0816	1.13	157.85
CONWIP	99.361	7.2533	0.0941	1.30	164.24
DWIP	99.475	7.2617	0.0766	1.06	130.33
Kanban	99.492	7.2629	0.0782	1.08	124.75
CPLC	99.936	7.2953	0.0436	0.60	92.36

Table 4: Simulation results summary.

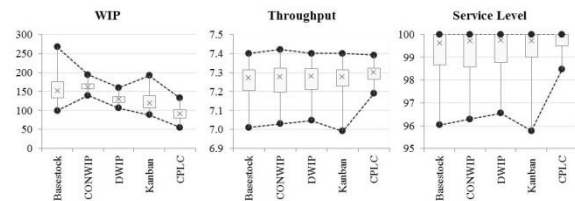


Figure 10: Comparison of WIP, Throughput, and Service Level

Statistical comparison of the simulation results for service level and throughput allows concluding that CPLC outperforms the other models with a significance level of 1%. However, the hypothesis tests show that it is not possible to conclude that there are statistically significant differences in service level and throughput within the group of Kanban, DWIP, CONWIP, and Basestock. Analysis of results in terms of WIP show statistically significant differences among three clusters: CPLC (lowest WIP level), Kanban and DWIP (intermediate WIP level), and CONWIP and Basestock (highest WIP level). Table 5 shows the result of the hypothesis test comparing the model in the row with the model in the column, for the specified indicator.

	Service Level				Throughput				WIP			
	Base stock	CONWIP	DWIP	Kanban	Base stock	CONWIP	DWIP	Kanban	Base stock	CONWIP	DWIP	Kanban
CPLC	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
Kanban	⊗	⊗	⊗		⊗	⊗	⊗		⊙	⊙	⊗	
DWIP	⊗	⊗			⊗	⊗			⊙	⊙		
CONWIP	⊗				⊗				⊗			

⊙ Statistically significant difference    ⊗ No statistically significant difference

Table 5: Statistically significant test results at 0.99 confidence level (one sided).

The objective of CPLC is fourfold: improve (1) throughput and (2) service level, while simultaneously reducing (3) throughput variability and (4) WIP. From the simulation results, it can be inferred that CPLC reduces variability, measured as the standard deviation expressed as a percentage of the mean. A one-sided F-

Test comparing the standard deviations of the analyzed methods validates this conclusion (Table 6).

	Throughput Variability			
	Base stock	CONWIP	DWIP	Kanban
CPLC	○	○	○	○
Kanban	✗	✗		
DWIP	✗	✗		✗
CONWIP				
Base Stock		✗		

○ Column methodology's variance is larger than row methodology's variance  
✗ No statistically significant difference

Table 6: Statistically significant test results at 0.99 confidence level (one sided).

The statistical comparison shows that CPLC yields a lower variance, hence a lower variability, when compared to the other methods.

### 5. CONCLUSIONS

Production line control under uncertainty conditions requires a highly adaptive and anticipative methodology that enables collaboration between the different components of the line to overcome failures and maintain high throughput while keeping WIP low. Traditional models for buffer management and production control lack the required characteristics. The proposed methodology, CPLC, based on CCT's principles, constitutes a more advanced and complete solution approach allowing both adaptability and anticipation, more suitable to face the challenges of high volume production line control under uncertainty.

Based on the observations made during the simulation runs and the conclusions for the case study, the methods analyzed can be classified as shown in Table 7. Statistical comparisons of the results in this case indicate that CPLC outperforms Base-stock, CONWIP, DWIP and Kanban in terms of service level with a significance level of 1%. Also, the hypothesis tests show that it is not possible to conclude that there are statistically significant differences in service level within the group of Kanban, DWIP, CONWIP and Base-stock. The statistical analysis also allows clustering models in three performance groups in terms of WIP; i.e. Base-stock and CONWIP, DWIP and Kanban, and CPLC, with a difference at significance level of 1%. As for throughput variability, it can be concluded that CPLC reduces variability, measured as the ratio between throughput standard deviation and mean. Performing the statistical comparison for comparing CPLC with the remaining methods shows that variability is reduced in every case.

Experimental conclusions, though validated only for the real system data analyzed in the case study, may be applicable to other systems and configurations, but further studies to generalize the conclusions are required.

		Rank	Major merits or contributions of the model
Methodology	CPLC	1	<ul style="list-style-type: none"> <li>• Early conflict detection capabilities to reduce WIP and minimize throughput variability</li> <li>• Dynamic buffer level and process rate selection based on real-time system status</li> </ul>
	Kanban	2	<ul style="list-style-type: none"> <li>• Minimal WIP to yield same throughput as models ranked 3 and 4.</li> <li>• Pull system (production is pulled by demand)</li> </ul>
	DWIP		<ul style="list-style-type: none"> <li>• Minimal WIP to yield same throughput as models ranked 3 and 4.</li> <li>• Shows impact of dynamic adjustment of parameters in WIP reduction</li> </ul>
	Basestock	3	<ul style="list-style-type: none"> <li>• Simple control method, easy to implement</li> </ul>
	CONWIP	4	<ul style="list-style-type: none"> <li>• Simple control method, with demand pull.</li> <li>• Introduces simultaneous control of all buffer spaces to optimize the system's performance</li> </ul>

Table 7: Methods ranking and contributions summary

A protocol for extending CPLC into control of CSNs has been introduced. The proposed protocol embeds CPLC into the organizations that compose the SN; therefore the advantages of the CPLC methodology are expected to influence the overall performance of the supply network.

### 6. FUTURE RESEARCH

The case study results show that production line control based on CCT can produce relatively high line performance while keeping low WIP levels in high volume production lines under uncertainty conditions. However, CPLC is still a theoretical methodology and future research should define the necessary requisites for it to be viable for implementation in plants. Moreover, more complex path evolution analysis models can be integrated into CPLC to extend its prediction accuracy, enabling it to reach better control decisions.

Experimental analysis to estimate the potential benefits of the extension of CPLC to CSNs must be performed to validate the proposed protocol.

### ACKNOWLEDGEMENT

This research has been developed with partial support from the PRISM (Production, Robotics, and Integration Software for Manufacturing & Management) Center at Purdue University.

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