Improving Manufacturing Performance by Standardization of Interprocess Communication

Javier Villalba-Diez and Joaquín Ordieres-Meré

***Abstract*—A number of environmental forces such as increasing value chain network complexity, decreasing product life-cycle cost, and time-to-market requirements or increasing product complexity act upon manufacturing organizations, enhancing the acute need for organizational routines that foster efficient and effective communication between processes. Such organizational routines erode quickly in the absence of common standards for knowledge sharing, that is why successful manufacturing systems benefit from interprocess standardization. The purpose of this paper is to offer a standardization model of interprocess communication that increases manufacturing operational performance (MOP). First, we propose a novel holistic model that makes standardized interprocess communication possible in manufacturing organizations. Second, we propose a model for quantifying the implications of standardizing interprocess communication upon MOP. Finally, as a matter of application, we show the results of its successful implementation in one Japanese manufacturing organization.**

***Index Terms*—(CPD)nA, holonic systems, interprocess communication, manufacturing performance, process standardization.**

I. Introduction

INCREASING structural value chain network complexity [1], pressing product life cycle cost and time-to-market requirements [2] or rising product complexity [3] are some of the environmental forces acting upon manufacturing organizations. When structural complexity increases, organizations tend to develop interfaces between processes [4] in order to make information readily available for process owners (POs) [5]. Those forces applied upon these new interfaces enhance the acute need of integrating and coordinating complex systems, and this brings with it the challenge of attaining more efficient and effective communication between processes. These challenges can be successfully accomplished through the standardization of a common language to connect processes within an organizational network. Such a language can be understood as an interprocess standard.

Although existing research emphasizes the need to standardize intraprocess management [6] capabilities, it faintly identifies the need to standardize interprocess communication. The standardization of interprocess communication is important because, as both theoretical [7] and empirical [8] research suggests, an organization's competitive advantage can erode quickly in the absence of common standards for knowledge sharing. Knowledge sharing "is the fundamental means through which employees can contribute to knowledge application, innovation, and ultimately the competitive advantage of the organization" [9].

This study addresses this gap in research by asking the following two questions. First, can we find a communication process that aligns interprocess communication in one single standard? Second, in order to be shown worth implementing, can we suggest a quantitative relationship between the implementation of such standard and manufacturing operational performance (MOP)?

The literature on process standardization serves as a framework for our research because it allows us to analyze how interprocess communication was developed as well as its evolution. The review on knowledge sharing in manufacturing organizations narrows our scope upon the conditions for this standard to emerge in manufacturing organizations. The literature review on Plan Do Check Act (PDCA) serves as platform for the fundamental paradigm shift and first contribution proposed in this paper: from the classical Deming's PDCA as problem-solving method toward PDCA as interprocess communication standard. An examination of interprocess organizational relationships together with the identification of the nature of the knowledge sharing channels will enable the desired standardized interprocess to be achieved. The second contribution of this paper focusses upon proposing a mathematical model that quantifies the link between interprocess network structure and MOP.

The structure of the paper hereinafter continues with a section devoted to the literature review in which we present a brief review on process standardization from an interprocess communication perspective within an organizational network paradigm and its impact upon MOP. The current understanding of PDCA. Second, based upon new perspectives on PDCA as interprocess standard, we present a framework that allows for standardized interprocess organizational information exchange. Third, within this framework, we propose a theoretical model that facilitates the quantification of the effect of interprocess standardization routines upon MOP. Fourth, we present the results of our field research with one case study in a Japanese manufacturing facility. Afterward, we discuss and interpret the field results and discuss the alignment of the field results with the theoretical model. Finally, the last section presents the conclusions from the research and encourages further research in the field.

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TABLE I
PROCESS MANAGEMENT FROM AN INTERPROCESS PERSPECTIVE

Reference	Key Findings in Process Standardization	Interprocess Interpretation in Manufacturing Environments	Impact upon MOP	What needs to be done?
[6]	Process standardization is understood as "the unification of variants of a given business process by aligning the variants against an archetype process"	The interprocess standardization is implicitly operationalized so as to simplify and reduce the typology of interfaces between processes, avoiding hence variants and maintaining a unified communication mechanism. This is desirable in a manufacturing context for instance when several facilities perform the same or similar processes and management aims to foster **benchmarking** as shown in this example [17].	[6] show the positive influence of standardization on process performance. Evidence of the importance of cooperative benchmarking upon MOP and the relevance of the human factor within it has been shown by scholars [18]	The human factor is hardly analyzed in these approaches. The conditions for knowledge sharing in order to unify and align processes are not discussed by these scholars..
[19]	Process Standardization focuses upon interchangeability of processes so as to ensure the functionality of the outcomes.	The interprocess standardization is subordinated to the product standardization in order to attain the ultimate **interchangeability** of products as shown in [20].	Product interchangeability is operationalized for instance through product modularity allowing to "introduce many successive versions of the same product line with increased MOP levels" in manufacturing facilities [21].	
[22]				
[23]	Process standardization is understood as unification process and identifies the need to manage interprocess information	Interprocess standardization management is acknowledged as a management task. The solution proposed passes through a process taxonomy that clusters processes depending on several factors such as uncertainty or repeatability following [24].	The definition of standards upon shopfloor activities with high repeatability is regarded as a key method to improve MOP [25].	The need for a **holistic inter-process communication standard**, independent of the process nature becomes explicit. **One of the contributions of this paper aims to fill this research gap**.
[26]	Process Standardization is defined as "the activities in which people develop bases or rules for measuring such processes and so develop codes of conduct by establishing regularity from disorder".	From an interprocess standardization this perspective focuses upon the behavioral aspects of standardization. Ping's definition has the same goal as the aim [27] see in Lean Management: "Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability."	According to [27] The impact of lean management has proven highly efficient when increasing MOP [27].	[27] propose a multifaceted view upon Lean Management and hence upon the effort of reducing process variability. We believe that these multifactorial, explained in a number of tools/methods, need and can be standardized with the help of a holistic interprocess standard that is presented in this paper.
[28]	Toyota's usage of Plan-Do-Check-Act (PDCA) cycle process standardization is described as "basis for continuous improvement" and as one of its strategic competitive advantages.	From an interprocess standardization perspective, Toyota implicitly performs interprocess communication as an "**evolutionary learning capability**" of capability development, better known and operationalized as 底展開 or Yokotenkai [7].	The benefits that such evolutionary learning capabilities upon MOP have extensively and intensively been studied by scholars [29].	PDCA is understood as problem-solving technique. The current focus of PDCA will be presented later in the literature review. **Our contribution in the next section will expand this view**.

II. LITERATURE REVIEW

A. *Interprocess Standardization and Its Impact Upon MOP*

Process standardization is performed on an international level by international standards bodies such as the ISO, the IEC, and the IEEE [10]. Extensive and intensive research defines process standardization from several angles. In Table I, we summarize a literature review of process standardization from an interprocess point of view and its impact upon MOP from the perspectives of different scholars, as well as the shortcoming related to these perspectives. We also propose necessary actions to be taken and explain how this paper will tackle these research gaps.

B. *Conditions for Knowledge Sharing in Manufacturing Operations.*

The knowledge management guru Ikujiro Nonaka introduces the concept of 場 "ba" in Japanese to explain the context for knowledge sharing [11]. "Ba" is a shared context that enables the emergence of knowledge sharing out of interaction between people [12]. We list the conditions proposed by these scholars and concretize them for a manufacturing operations special case.

1) The first condition is that "ba" must be "self-organized and possess its own intention, objective, direction, and mission."
2) The second condition is that "ba" requires "participants with different types of knowledge."
3) The third condition is that "ba" needs "open boundaries."

In the context of manufacturing systems, the first condition (1) can be jointly achieved through the powerful paradigm of holonic manufacturing systems: an organizational framework that describes manufacturing organizations as robust and evolvable networks of autonomous holons that interact as a system. Tharumarajah *et al.* [13] proposed for the first time the use of the concept of holon, an autonomous cooperating agent, to be applied in the context of manufacturing systems. A group of holons that act together is called a holarchy. Holonic systems have the advantage of robustness against disturbances derived from the hierarchical organizational topology [14] and the global performance evolutionary functionality derived from the heterarchical process-oriented dynamic connectivity patterns [15]. Regarding the second condition (2), holarchies ought to share knowledge along the value stream [16] allowing for different departmental/hierarchical holons to exchange their different perspectives on a shared issue. The third condition (3) suggests that in order for knowledge sharing to thrive we need a holonic context focused in a certain value-stream-oriented direction toward certain goals that leaves room for individual self-fulfillment. Nonaka *et al*. [11] do not provide any practical model to foster such conditions. We believe that PDCA can provide such context: therefore the following PDCA literature review discusses the current understanding of PDCA in order to later examine it in more depth.

C. PDCA State of the Art

Our research has identified four currents schools of thought that have the PDCA cycle as the central unit: 1) PDCA as a problem-solving pattern; 2) PDCA as an empowerment behavioral pattern; 3) PDCA as a project management pattern [30], [31], [32]; and 4) PDCA as a strategic leadership pattern [33]–[36]. Our literature-review focuses upon the first two approaches.

1) *PDCA as a problem-solving pattern:* Edward Deming [37] popularized PDCA as the “Shewart Circle” in Japan as an iterative problem-solving method based upon Bacon’s (Novum Organum, 1620) scientific method of “hypothesis–experiment–evaluation” or plan: developing an hypothesis-do: conducting the experiment-check: evaluating the results. Toyota developed Deming’s ideas [38] and added the Act Phase as interpreting the results. Other companies [39] have made use of PDCA as a problem-solving pattern as well and have developed IT cloud-based solutions to speed up the problem-solving performance by enhancing cooperation between its users. [40] understands PDCA mainly as a problem-solving technique to develop critical thinking.
2) *PDCA as an empowerment behavioral pattern:* The development of critical thinking through PDCA has given Toyota a strategic competitive advantage because it has fostered an organizational capability of capability development [7]. Rother [41] describes Toyota’s capability development behavioral pattern with the concept of KATA. For Rother, skill comes from repetition, and although the concept of KATA is not new to the business environment [42], he was the first to link it to an industrial environment. This concept is based on continuous improvement toward a “target condition,” and so the PDCA should lead from the process’s current condition to the desired target condition.

Both previous approaches have an inextricable connection: problem solving is used by organizations to empower its people to achieve certain goals. However, these understandings of PDCA do not consider the fact that organizations are complex adaptive systems [43], and their ever-increasing structural, functional, and organizational complexity [44], makes any attempt to describe “future states” or “goals” on an organizational basis futile. The reason for this is simple: actions upon processes can potentially influence all other processes simultaneously. Therefore the PDCA will serve to the empowerment when it is understood as the previous mentioned scholars. At an organizational level, complexity will take over and this PDCA approach solely might not be enough to explain organizational success.

In the light of these shortcomings, we propose a novel interprocess communication holon based upon PDCA.

III. STANDARDIZATION MODEL

A. Interprocess Communication Holon: (CPD)nA

We propose following interpretation of the PDCA cycle as interprocess communication standard between POs.

1) *Check or Commitment or Consensus:* In the Check phase, there are three subphases. First, the process at Gemba [45] is studied. Second, consensus is reached upon how success is to be achieved by establishing a process key performance indicator (KPI) for the sender PO that measures process performance. It is important for creating psychological empowerment that the receiver PO explains why such a KPI is necessary for success in order to create meaningfulness for PDCA in sender PO. Finally, the current state of this KPI is measured. This phase creates fairness and transparency through commitment and a commonly agreed-upon set of expectations.
2) *Plan or Process–Priority–Analysis or Active Learning:* In the Plan phase, active learning happens. In this phase, there are three subphases. First, the current state of the process using a process mapping tool is understood [46]. Second, the main sources of MUDA, MURA, and MURI (3M) are prioritized [47]. Finally, the main source of the 3M’s within the process boundaries are analyzed.
3) *Do or Action:* In the Do phase, we act upon the process. After deciding why they occur, the PO defines an action upon the process in order to sustainably eradicate the source of the 3M’s. It is important to enhance here the interdependent nature of processes; overtime, action is taken upon the process, the whole process might change. Therefore we recommend implementing only those actions simultaneously whose effect in the process does not affect other actions also.
4) Repeat 1) to 3).
5) *Act or Anchor Active Learning or Standardization:* The Act phase is where anchoring and transforming the active learning into organizational learning. After reaching a plateau in the KPI, the knowledge developed throughout process management is anchored into a Standard. If the actions taken upon the process delivered a positive effect in the KPI, these changes in the process will be integrated into the new current state, hence becoming the new standard, understood as the best-known way to perform the

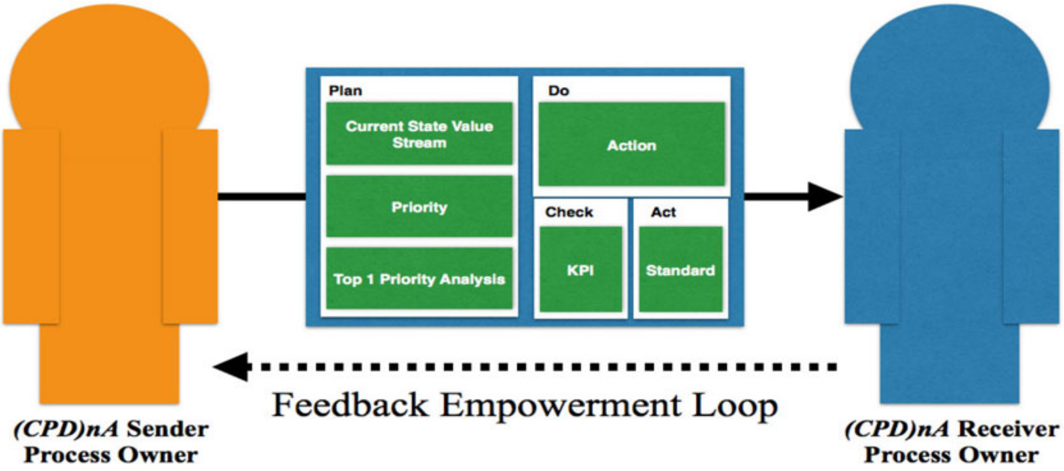

Fig. 1. (CPD)nA as interprocess communication pattern between POs.

process. If the action upon the process delivered no results, then the standard is not changed. It is the responsibility of the receiver PO to ensure that the sender PO performs the process following the standard.

Hence, the method we are proposing is not PDCA but C-P-D-C-P-D-C- . . . -A; therefore, it will be designated by (CPD)nA. This process management procedure is aligned with the theory of constraints (TOCs) [48] where the current state of processes are first understood, in order to systematically eradicate the biggest constraint that hinders the process achieve better performance.

(CPD)nA is an interprocess communication framework that is able to steer and guide the continuous improvement of the process through the communication upon process performance to the (CPD)nA receiver. This autonomous communication process owned by the (CPD)nA sender is performed in cooperation with the (CPD)nA receiver and is the nucleus of the continuous learning process. It is based upon the empowerment of each PO within each individual value creating context. As a part of the empowerment process, each (CPD)nA sender, with the support given by the (CPD)nA receiver, requests to the organization the necessary resources for the process management from the organization.

The idea of PO is central in our proposal because it defines the role of each person in the organization as a capable individual that has the responsibility of increasing value by managing the assets that have been put by the organization to his/her disposal. The (CPD)nA sender is responsible for the process and owns the (CPD)nA. The (CPD)nA receiver is responsible for providing sufficient motivation for the (CPD)nA sender to review the Plan phase. The feedback given by (CPD)nA receiver should be taken into consideration in order to prioritize potential sources of misalignment and select those that should be acted upon in the Do phase (see Fig. 1).

The only pillars we propose within the (CPD)nA model are:

1) our will to continually improve the process, KAIZEN [47];
2) our understanding of the current state of the processes at stake.

These make this algorithm more robust and evolvable than those presented before. We will later discuss the management implications in terms of this (CPD)nA standard provides.

After describing (CPD)nA as an interprocess communication standard, we define the structural network that emerges when linking POs with (CPD)nAs.

B. Interprocess Information Exchange Structural Network

Manufacturing organizations can be understood as networks under the "organizational network" paradigm [49]. A network is a set of objects (called nodes or vertices) that are connected together. The connections between the nodes are called edges or links. In mathematics, networks are often referred to as graphs. One can formally define a graph as $G = (N,E)$, consisting of the set N of nodes and edges of set E, which are ordered if the graph is directed.

We define an interprocess information exchange network as organizational structural directed graph as a set of nodes formed by the processes, represented by their related POs, of the organization and a set of edges formed by (CPD)nAs that are reported from several POs to others.

Dynamically evolving networks are the subject of intensive research [50]. The growth of such a network and the increasing linkage of POs with each other is expected to happen following a hierarchical or value-stream-oriented preferential attachment rule [51]. This happens when the probability of (CPD)nA connection of a given PO is higher with that of other POs with whom a person exchanges vital information to support the value creation.

The (CPD)nA standard allows for interprocess connections inside or outside the organizational boundaries such as relationships with coworkers, management, suppliers, customers, and practically any stakeholder. However, given that the PO as responsible for a certain process and given that this responsibility is univocal (i.e., one PO is responsible for one process), topologically speaking, each (CPD)nA has only one source and one sink: one sender and one receiver. This system allows for several (CPD)nA from one Sender to the same or different receivers, denoting that the performance of one PO can be measured from different KPI perspectives.

After describing the structural network, we propose a mathematical model that quantifies topological properties of this network and links it to MOP.

C. Mathematical Argumentation of Model Quantification

Complex networks and their properties are almost always quantified by the combination of two key parameters: clustering coefficient (CC) and the average path length (APL) [52]. CC is a measure of the degree to which nodes in a graph tend to form clusters or cliques of "all-connected-with-all" groups. It seems self-evident that in networks, people tend to exchange information with those other agents they are explicitly or implicitly connected with, therefore, given a set of nodes Ni, our aim is to increase the CC of this set to increase the information exchange in the network. APL is the average number of steps along the shortest paths for all possible pairs of network nodes. If the APL is high, then information will take many steps, and more time, to get from one node to another reducing the network's ability to exchange knowledge. We seek then for configurations with a high network CC and a small APL. These networks are dubbed "small-world" networks (SWNs) [53].

SWNs are a class of networks that are highly clustered, like regular lattices, yet have small average path lengths, like random graphs. CC and APL are combined in the novel measure of "small-worldness" *w* given by Telesford *et al.* [54] who propose a small-world metric, *w*

$$w = \frac{\mathrm{APL}_{\mathrm{rand}}}{\mathrm{APL}} - \frac{\mathrm{CC}}{\mathrm{CC}_{\mathrm{latt}}}. \tag{1}$$

This metric *w* compares network clustering (CC) to an equivalent lattice network (CClatt) and path length (APL) to a random network (APLrand). That is why values of *w* close to 0 denote high "small-worldness," values of *w* close to 1 denote high randomness and values of **w** close to –1 denote high regularity. We will find this metric useful for representing the dynamic implications of interprocess communication standardization upon MOP measured by the internationally accepted performance indicator hours per vehicle (HPV) [55].

The proposed model advocates for a correlation between the evolution of *w* with changing interprocess (CPD)nA connectivity and the MOP of the overall facility.

When complex networks learn tasks, the learning process is mathematically modeled by a sigmoidal "*S*-curve" [56]. We expect therefore a sigmoidal "*S*-curve" relationship between performance and network small-worldness. The generalized mathematical expression of the sigmodial curve or Richard's curve [57] allows for flexible *S*-shaped curves. The interpretation of the parameters is as follows:

$$\mathrm{HPV}\,(w) = A_1 + \frac{K_1}{\left[1 + Q_1 \cdot e^{-B_1 \cdot (w - M_1)}\right]^{\frac{1}{Q_1}}} \tag{2}$$

where A_1 represents the lower asymptote of HPV (best performance) after optimization, K_1 represents the variation of *w* throughout the optimization, B_1 represents the performance optimization rate of HPV in terms of 1/*w*, and Q_1 represents a coefficient that influences the gradient of the curve, M_1 represents the value of *w* of maximum HPV optimization rate.

For sigmoidal learning curves the first derivative (optimization rate) has a bell-shaped form, as supported by experimental evidence [58]. This bell-shaped form naturally explains the presence of a learning effect that can be explained in three phases: awareness, learning, and maturity.

1) In the initial **awareness** stages of process management standardization, the organizational network starts exchanging information in a standardized form, and although the network's randomness decreases (*w* becomes smaller than 1), there is no a major impact on performance. Therefore HPV does not reduce significantly.
2) With increasing interconnectivity **learning** occurs. As clusters increase in size and path length decreases, the network's similarity to a small-world increases, and so *w* comes closer to 0. We then expect a faster reduction rate of HPV in relation to *w*. In other words, the second derivative of HPV(*w*) is expected to be closest to zero for values of *w* close to zero

$$\left.\frac{\partial^2 \mathrm{HPV}(w)}{\partial w^2}\right|_{w_0 \approx 0} \approx 0. \tag{3}$$

3) The **maturity** phase starts when the network's connectivity increases further. The network's topology becomes more similar to a lattice network (values of *w* closer to 1) and the network performance variation is expected to become flat again: the harvest has grown to maturity and is starting to die out.

In the same line, resembling the cited learning process happening in complex networks, we expect a sigmoidal relationship between the connectedness of the network *C* and manufacturing performance HPV given by the mathematical expression

$$\mathrm{HPV}(C) = A_2 + \frac{K_2}{\left[1 + Q_2 \cdot e^{-B_2 \cdot (C - M_2)}\right]^{\frac{1}{Q_2}}}. \tag{4}$$

The interpretations of the parameters are very similar. Here, A_2 represents the lower asymptote of HPV (best performance) after optimization, K_2 represents the variation of *C* throughout the optimization, B_2 represents the performance optimization rate of HPV in terms of 1/*C*, Q_2 represents a coefficient that influences the gradient of the curve, and M_2 represents the value of *C* of maximum HPV optimization rate.

Summarizing, we predict a maximum optimization rate with structures similar to SW topologies and a higher performance with more amount of explicit standardized process oriented information exchange.

IV. DISCUSSION AND MANAGEMENT IMPLICATIONS

After having described (CPD)nA as interprocess communication holon, the resulting structural network extrapolation and proposing a mathematical quantification of its impact upon MOP, we now state the following propositions as management implications:

Proposition 1: (CPD)nA as an interprocess communication standard. (CPD)nA, understood as interprocess communication

TABLE II
KPI DESCRIPTION IN CASE STUDY SAMPLING

KPI	Description
HPV	The overall facility HPV was measured taking into consideration all workers (blue collar and white collar).
Connectedness (C)	Number of (CPD)nA interprocess connections between all POs
Small-worldness (w)	Small-worldness of the (CPD)nA interprocess network

standard can be used to standardize all sorts of processes, avoiding the need for a process taxonomy proposed by [24]. Furthermore, it fulfills all necessary conditions for knowledge sharing proposed by [11]: first, linking POs in a holonic network in an evolvable and robust manner; second, combining their knowledge along the value stream; and third, providing open boundaries for unfolding PO capabilities. Additionally, it serves as an optimization pattern for solid empowerment and continuous improvement, not based upon "target states," but upon the shared value of KAIZEN [47]. Finally, it serves as an interprocess standard, reducing the variability of processes and hence establishing regularity from disorder [26].

Proposition 2: (CPD)nA as a holon to build structural organizational network. (CPD)nA, understood as an interprocess standard, provides the smallest unit of a network that, if extrapolated, can be used to design the structure of manufacturing organizations as holonic manufacturing systems.

Proposition 3: Structural small-worldness increases organizational learning rates. Fastest learning rates are achieved with w values close to 0 in the (CPD)nA structural network. This indicator ought to help leaders design organizations for better knowledge sharing and steer empowerment efforts toward better MOP.

In the next section, we present a case study that will show an application of the proposed model and analyze the relationships observed.

V. CASE STUDY

To clarify our discussion and as a first step to evaluate the interprocess standardization and its value impact upon MOP, we use a within-case study. As argued in [59], a single study is only one piece of a puzzle to unlock the knowledge contained in that area. The construct proposed here can only be seen as a possible building block in the process to develop validity and reliability of the model, as well as increased generalizability.

Following the recommendations given in [60], we follow a clear case study roadmap. This roadmap has several phases: 1) scope establishment; 2) specification of population and sampling; 3) data collection; 4) standardization procedure; 5) data analysis; and 6) case closure.

A. Scope Establishment

We aim to study the implementation process of (CPD)nA as interprocess standard, the extrapolation to a structural network with hierarchical and value-stream-oriented preferential attachment, and the implication of such a process and MOP measured in HPV.

The company selected for the case study is a Japan-based engine manufacturing facility that will be called MotorCo for reasons of anonymity.

B. Specification of Population and Sampling

The facility presented a workforce of 500 people and 34 managers distributed within three management levels E1–E2–E3 being E1 the highest in hierarchy. The interprocess standard (CPD)nA was implemented within the 34 managers and the evolving dynamics followed a hierarchical and value-stream oriented preferential attachment.

C. Data Collection

One of the authors was involved in MotorCo's interprocess standardization activities that started in July 2012 and ended in June 2014. Subsequently, the case study is based on a large number of data over 24 months. On a monthly basis, Table II shows the KPIs measured in Gemba Walks [45].

The actual implementation of the (CPD)nA interprocess standardization was left to the responsibility of the POs. It was observed that POs tended to (CPD)nA connect preferably other POs with whom the had either hierarchical or value-stream-oriented relationships.

We assume that the majority of manufacturing facilities worldwide have a performance management system. The topological characteristics C and w of the structural organizational network (CPD)nA were mapped through a monthly checking of how many (CPD)nA connections were performed by whom. Hence, the replicability of this within-case study is possible given a performance management system and a regular (CPD)nA network mapping.

D. Standardization Procedure

In order to implement the interprocess standard (CPD)nA in all POs relationships, MotorCo conducted an ongoing empowerment effort. This empowerment process went through different phases: awareness, learning, and maturity, as described in the theoretical model.

1) In the **awareness** phase, all POs involved (34 managers) were made aware of the intention of senior management of standardizing interprocess management communication and were acquainted with the new (CPD)nA procedure. This was made through a series of two-day workshops. This process took about three months and a performance increase was still not visible.
2) In the **learning** phase, all POs were supported by experts in the implementation of (CPD)nA. The focus here

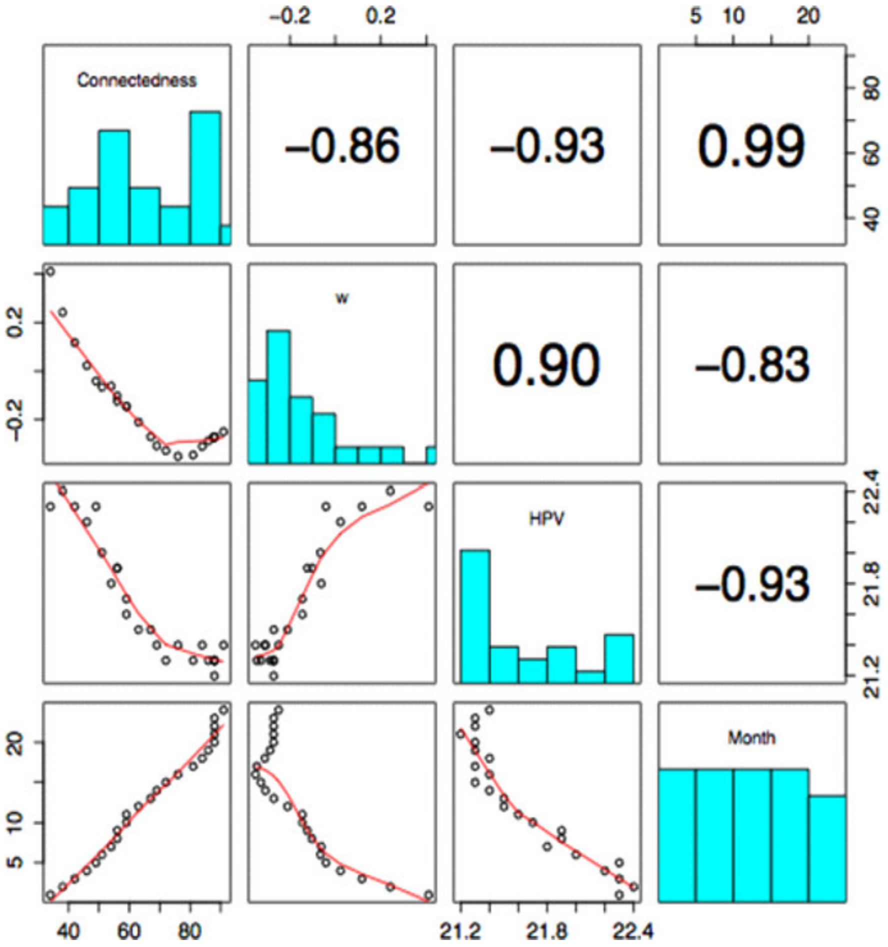

Fig. 2. Results of the case study.

was upon making sure that all POs strictly followed the procedure. Senior management needed to be explained about of the need to support the interprocess standardization with discipline and not increase the pressure for results that would hinder the learning process. This process took about 14 months and a performance increase was sustained. In the **awareness** and **learning** phases, the necessary conditions for knowledge sharing are created. In the **maturity** phase, these conditions are sustained.

3) Once empowered in the usage of (CPD)nA, in the **maturity** phase, all POs performed the interprocess standard as described. The difficulty in this phase was to maintain the homogeneity of the standard. For this reason, on quarterly basis, all POs were gathered and best practices (CPD)nA were presented for feedback-bashing purposes. This useful feedback kept the standardization process vigorous.

E. Data Analysis

The gathered data are represented in Fig. 2.

These results confirm the proposed model in this particular case.

1) Not only the values of *HPV*, *C*, and *w* have a remarkably high correlation as shown in the previous figure, HPV(*w*) and HPV(*C*) empirical values can also be regressed with (5) and (6), respectively, to Richard's sigmoidal curve, which resemble the learning process through increased explicit connectivity. Both regression equations present a fairly high level of confidence, represented by $R^2 > 0.9$

$$\begin{aligned}\mathrm{HPV}(w) &= 21.1896 \\ &\quad + \frac{1.1104}{\left[1 + 239.86 \cdot e^{-1750\cdot(w+2.88\cdot 10^{-2})}\right]^{\frac{1}{239.86}}} \\ R^2 &= 0.94 \qquad (5)\\ \mathrm{HPV}\,(C) &= 21.2738 \\ &\quad + \frac{106.0477}{\left[1 - 0.5502 \cdot e^{1.59\times 10^{-3}\cdot(C-288.9)}\right]^{\frac{1}{0.5502}}} \\ R^2 &= 0.92. \qquad (6)\end{aligned}$$

2) Maximum optimization rate in HPV(*w*) is achieved when the structural interprocess network is very close to a small-world network with $w_0 = -0.0288$ as expected.

$$\left.\frac{\partial^2 \mathrm{HPV}(w)}{\partial w^2}\right|_{w_0 \approx -2.88\times 10^{-2}} \approx 0.$$

F. Case Summary and Limitations

1) Case Summary: MotorCo achieved two very important goals with the standardization of its interprocess communication.

First, comparing the actual results MotorCo achieved an optimization in HPV of 4% in 24 months, which is a tremendous improvement considering the high level of standards given in the facility at the beginning of the study.

Second, and even more important than the actual degree of optimization, was the fact that the optimization was sustainable as shown intuitively in the "*S*-curve." Both curves HPV(w) and HPV(C) show that the MOP optimization endures and is sustainable. The model is hence robust in ensuring lasting performance benefits through the standardization of process-oriented communication.

These results are in agreement with previous research performed in the manufacturing industry [61] that show that knowledge management has a positive correlation with operating performance. The results are in line with previous research that demonstrates the importance of manufacturing practices in predicting manufacturing performance [62]–[65].

These results suggest that the case covers two important interprocess standardization effects, MOP optimization and sustainability, and indicate that the model can indeed be sufficiently relevant to pursue further research.

2) Limitations: One single case study is not enough to claim general validity of a model. At its best, it can provide practical insights that would be otherwise difficult to present from a theoretical perspective. In particular, two limiting aspects are worth mentioning in order to temper the results.

First, the time frame of 24 months used in the study was relevant in this particular case given the size of the structural (CPD)nA network created, the product complexity presented high technological challenges throughout the interprocess improvement and the Japanese culture of consensus seeking decision making. The authors expect replicable dynamics but different time frames could be used in other circumstances.

Second, the correlations shown in the case study are robust, but correlation does not imply causation. It cannot be inferred from one single case study that the interprocess standardization alone causes HPV optimization; the high correlation only explains a large part of the variance. Therefore, every possible causative relationship such as organizational size, product complexity, people empowerment level, or company culture should be analyzed.

VI. CONCLUSION

This paper provides a systematic understanding of the role and value impact of interprocess standardization through a new model called (CPD)nA.

In this paper, we have presented a framework for interprocess standardization through (CPD)nA algorithm in manufacturing environments. A mathematical model for understanding and measuring the impact of implementation of this interprocess standardization routines in MOP has been as well outlined.

The model shows that there exists a high quantifiable correlation between MOP and small-worldness as well as MOP and process-oriented standardized connectivity of the organizational network. The resemblance between the learning behavior of organizational networks and complex networks is also demonstrated. Finally, the model indicated that higher levels of interprocess-oriented standardized connectivity are highly desirable in manufacturing environments.

A practical case study of a Japanese manufacturing facility was presented as a way of showing how the model works and can be implemented in practice.

This newly developed organizational framework allows leaders and decision makers to be informed regarding the potential behind the (CPD)nA standardization of interprocess communication. It can be expected that the application of this (CPD)nA interprocess standardization framework shall bring additional knowledge to better understand the impacts of the combination of structural and functional connectivity in the quest toward manufacturing operational excellence.

We encourage further research in this direction through an increase in sample size in order to prove causation. We strongly believe that the (CPD)nA-based holonic interprocess standardization approach presented in this paper is a method worth replicating in further research because of the promising benefits it brings toward achieving manufacturing operational excellence. We are convinced that this model can be extended to other nonmanufacturing environments in process intensive industries such as services, healthcare, IT, finance, and many others.

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