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System-theoretical Approach to Fundamental Limits of Controllability in Complex Organization Networks

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Abstract. Organisation is fundamentally based on elaborating the equilibrium of two contradicting forces. An increasing degree of separation of work leads to specialisation and therefore significant increase of productivity in terms of time and cost. This advantage is compensated for by the therewith rising effort required to define, shape and delegate the subtasks to the different players and have them well-informed, coordinated and motivated to successfully contribute to the overall project. The well-known and common approaches to optimize division of work are mainly based on strict hierarchical structures like work breakdown structures in order to perfectly identify work-packages and their respective interfaces. Control loops are then established maintaining the certainty to achieve the previously defined results of the subtasks so that they will perfectly fit and will be ready to flawlessly form the total product. However, this traditional approach presupposes perfectly defined stable and separable systems as well as perfectly operating controlling mechanisms. As soon as some imperfection of either of these is given, which can be safely assumed in reality, the method is bound to fail principally. With this paper, we propose a system-theoretical framework modelling in particular a local imperfect however controlled situation and providing the principal limits on a mathematical basis as well as allowing for means for a practical approach. Organisations are represented by slightly contradicting systems while interactions as well as controlling mechanisms are given by first and second order differential equations according to the Theory of Systems. The resulting long-term behavior of the model, optimally avoiding oscillating and probably escalating development, indicates the principal limits of controllability. We find that the concepts of Lean Construction mainly address exactly these requirements and therefore find their formal justification including some quantitative framework.

1. Introduction

Organization is all about improving efficiency of production by implementing division of work [1, 2]. The common structural approach to developing appropriately matching work packages is based on hierarchical tree-structures using reduced but nonetheless non-ambivalent interfaces to superior as well as sub-ordered structural elements [3, 4, 5]. Not only recent development of understanding implies that this strict concept is bound to fail principally. Meanwhile, alternative approaches like self-deterministic management [6, 7], agile management [8, 9] and to some degree concepts of lean management [10, 11, 12], where definitions are less strict and interfaces more cooperative, are gaining more and more importance.

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Understanding the principle of incomplete contracts [13, 14, 15, 16] already states that no result nor consumption of resources can be perfectly determined in advance which would be absolutely required by a hierarchical approach to division of work [17].

The well-known Principal-Agent Problem [13] points out that a perfect description of work and respective supervision can only be gained at a price of an at least equivalent effort as if not outsourcing the package. Thus, the goal of organization is finding the second-best solution instead of hoping for a never occurring first-best solution. The second-best solution is then represented by the balance between control and tolerance [18].

Part of the concept of coordination is doubtless the implementation of control mechanisms to adjust processes to required results. However, even then, the definition of perfect results to compare with is required. Thus, coordination not only focusses on the agents' side in order to fulfil the given requirements but also needs to deal with the principals' inability to formulate the perfect determination of work package as a solution to a given problem. This situation resembles the V-model [6] controlling not only the quality of a solution, measured as deviation from then given plan, but also the applicability of the result to solving the given problem appropriately. The therewith demanded extension of the principle of control, being absolutely compatible with the traditional approach of governing, however, not only requires a significantly higher provision of controlling resources but higher controlling delays as well, since the goal comparison procedure resides on a much more abstract level than just comparing facts to a plan.

On this background, we state that perfect determination, e.g. based on strictly hierarchical approaches, is principally not possible, neither on the agents' side nor on the principals' side [19, 20, 21, 22, 23]. Therefore, the question is to be brought up, to which degree within an inevitably inconsistent system local contradictories can be ruled out by respective controlling mechanisms and where perfection reaches its limits given by fundamental rules.

2. Organisation Modelled as a System

In order to understand the behavior of an organization [24], modelling as a system is required, forming the system as a set of elements and respective (systemic) interactions [25, 26, 27, 28, 29]. This comprises not only physical elements but all imaginable elements to be processed in order to complete the project.

Broken down to the utmost level of detail, each element is represented by a single variable q_i forming the state vector $\overline{Q}$ while all interactions are given by linear differential equations as the second term of a respective Taylor series. The constant terms can be eliminated by linear transformation of the reference system to the state of equilibrium $q_0 = 0 \quad \partial\overline{Q} / \partial t = 0$. Higher order terms are neglected for this approach, linear superposition property of impact is assumed.

$$\overline{Q}_{t+dt} = \overline{Q}_t + \overline{F}(\overline{Q}) \rightarrow \frac{\partial \overline{Q}}{\partial t} = \overline{Q}_0 + A\overline{Q} + \ldots \text{(higher orders)} \tag{1}$$

where A is the adjacency matrix and $\overline{Q}$ the state vector.
Written as components we obtain:

$$\frac{\partial q_j}{\partial t} = \sum c_{j,i} q_i \tag{2}$$

3. Unruled Inconsistent Systems/Organisations

As long as the system is not contradictory [27], the differential equations lead to the trivial solution and the system stabilizes at a state $\overline{Q} = \vec{0}$ (zero vector). Inconsistency is given if multiple influencing nodes are driving a common target towards different values. Formally, within a linear system, the differential equations are superposed. However, if the influencing parameters $c_{i,j}$ are strong and the impact is not performed simultaneously but e.g. alternatingly, a nonlinear system is built and instabilities show up on the time axis.

Example (Principal-Agent Problem) [13]*:* Two partners (1 and 2) are not agreeing on a certain value q_j. The principal (1) expects and formulates a certain quality q_j for a sub-product, while the agent (2) provides only a different value, for whatever reason. He probably knows better due to his expertise or cannot do better due to the given circumstances. Then, over time this absolute value is determined by each of the participants according to their personal (valid, however inconsistent) definition somehow alternatingly and induces the respective consequences to the adjacent elements.

In this context, the temporary $q_j(t)$ value is simply set by the locally determining party. Since the differential equation refers to only a modification of the previously set value, this needs to be understood as a very strong and very fast adaption to the given value (i.e. notifying the inadequate value and immediately setting it).

Remark: If the adjustment process is slow compared to the alternating determination of the contradicting elements, the resulting value represents the average opinion. This situation is equivalent to both parties accepting the other side's value to some degree over time.

Such inconsistencies are represented by the average resulting fuzziness of system variables. As long as factually inconsistencies are existing, the system models the behavior correctly. This includes averaging as well as oscillating or even escalating development.

Obviously, the two determining elements (players) maintain no direct interaction, namely nothing in order to clarify the situation. Only if one of the players is officially declared to be wrong, or both agree on a common value, the discrepancy is solved. Such procedure, however, is based on both players to realize each other's position or at least resulting value and start an attempt to solve, which means establish a corrective interaction.

4. Introduction of Controlling Structures

If means of controlling are established, one or both of the disagreeing parties or possibly a third party is observing the value in question and comparing this to an expected value. Based on this knowledge, forces are implied to bring the value back to expectation. In terms of systems theory, this is the introduction of a loop, where some impact is derived from an observation of a value [30].

The mathematical representation of any short loop (one member only, the controller returns only proportional reaction) controlling loop is given by the most simple structure:

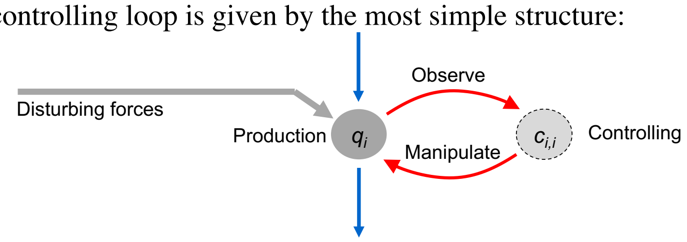

Figure 1. Basic System of a Theoretical Controlling Structure.

The general solution of this kind of equations is either oscillating, exponentially escalating or dampened, which is the preferred controlling behavior [31, 32].

$$\frac{\partial q_i}{\partial t} = c_i q_i \Rightarrow q_i \sim e^{c_i t} \tag{3}$$

The most general approach to understanding the time behavior of a starkly simplified subsystem of this kind is given by the differential equations for the harmonic oscillator. Any deviation of a value Q is answered by an automatized force leading back $-\beta$ to the desired value 0 working against the inertness μ towards any change and additionally taking some retarding forces ρ proportional to the rate of change into account.

$$\frac{\partial^2 Q}{\partial t^2} = -\frac{\beta}{\mu} Q - \frac{\rho}{\mu} \rightarrow \frac{\partial Q}{\partial t} - \omega^2 Q - k \frac{\partial Q}{\partial t} \tag{4}$$

using the damping factor $k = \rho / \mu$ and the frequency $\omega = \sqrt{\beta / \mu}$. The general solution is given by an approach of dampened oscillations as a complex function

$$Q(t) = Q_0 \cdot \exp(\lambda t) \quad \text{with } \lambda = -\frac{\rho}{2\mu} \pm \sqrt{\left(\frac{\rho}{2\mu}\right)^2 - \frac{\beta}{\mu}} := -\frac{k}{2} \pm \sqrt{\left(\frac{k}{2}\right)^2 - \omega^2} \tag{5}$$

Depending on the relationship between the damping factor $k = \rho/\mu$ and the frequency $\omega = \sqrt{\beta/\mu}$ this system is capable of performing dampened or escalating oscillations, as well as exponential approximating characteristics.

The situation of *weakly dampened oscillations* is determined by $k/2 << \omega$ where the root becomes negative and the solution therefore complex-valued. The frequency is different from the undamped frequency $\omega_A{}^2 = \omega^2 - k^2/4$ while the relaxation time is $\tau_R = 2/k = 2\mu/\rho$

Critical dampening refers to the situation where the root-term vanishes as no oscillations occur $k/2 = \omega \rightarrow \rho/2\mu = \sqrt{\beta/\mu}$. The solution reduces to a single exponential descent with an identical relaxation time constant $\tau_R = 2/k = 2\mu/\rho$:

Finally, the *overdamped case* is given if the root yields a real solution, i.e. $k/2 >> \omega$. The characteristic of the time development is also exponential, however, the time constant of relaxation is somewhat different.

$$\tau_R = \left[\frac{k}{2} \mp \sqrt{\left(\frac{k}{2}\right)^2 - \omega^2}\right]^{-1} \tag{6}$$

The primary solution (negative sign) indicates the damping factor $k/2$ reduced by a term depending on the relationship between frequency and damping factor and, thus, an increased relaxation time τ_R .

5. Theoretical Approach Applied on Delayed Integral Governors

Approximation of a Delayed Integral Controller

Understanding the characteristics of a harmonic oscillator obviously shows no direct connection to controlling mechanisms since terms like "inertia", "friction" and "retarding forces" have only symbolic meaning. However, from governing theory we know the principles of the integral controller as the most fundamental and stable concept.

$$\frac{\partial Q}{\partial t} = -k_C Q \tag{7}$$

The most influential parameter taken from real controlling systems which is not manifested here would be a significant time delay Δt resulting from finite detection patterns, lengthy considering and discussion procedures and, finally, from durations of initiation activities. Considering this parameter in particular, the DE takes on a different shape:

$$\frac{\partial Q(t)}{\partial t} = -k_C Q(t - \Delta t) \tag{8}$$

As a second order approach we substitute and develop $Q(t)$ in close proximity of t:

$$Q(t - \Delta t) \simeq Q(t) - \Delta t \frac{dQ}{dt} + \frac{\Delta t^2}{2} \frac{d^2 Q}{dt^2} + \ldots \tag{9}$$

Inserting this into the differential equation of the delayed integral controller yields finally

$$\frac{d^2 Q}{dt^2} = \frac{-2k_C}{k_C \Delta t^2} Q + \frac{2\left(k_C \Delta t - 1\right)}{k_C \Delta t^2} \frac{dQ}{dt} \tag{10}$$

This expression again needs to be compared to the harmonic equation

$$\frac{\partial^2 Q}{\partial t^2} = -\frac{\beta}{\mu} Q - \frac{\rho}{\mu} \frac{\partial Q}{\partial t} \tag{11}$$

Thus, we identify as a useful approximation using $\tau_C = 1/k_C$ as the time constant of the original governor:

$$\mu = \frac{\Delta t^2}{\tau_C} \quad \beta = \frac{2}{\tau_C} \quad \rho = 2\left(1 - \frac{\Delta t}{\tau_C}\right) \tag{12}$$

Characteristics of Delayed Integral Controllers
On this background, the behavioral cases of an integral controller with controlling strength $k_C = 1/\tau_C$ and subjected to some delay Δt can be formulated:

The *overdamped controller* is well capable to rule out any deviation, however not in the shortest possible time. The relaxation time is given by:

$$\tau_R = \left[\frac{k}{2} \mp \sqrt{\left(\frac{k}{2}\right)^2 - \omega^2}\right]^{-1} = \left[\frac{\rho}{2\mu} \mp \sqrt{\left(\frac{\rho}{2\mu}\right)^2 - \frac{\beta}{\mu}}\right]^{-1} = \Delta t^2\left[\left(\tau_C - \Delta t\right) \mp \sqrt{\tau_C{}^2 - 2\tau_C\Delta t - \Delta t^2}\right]^{-1} \tag{13}$$

Developing the full term for $\Delta t^2/\tau_R << \tau_C - \Delta t$, i.e. a controller time constant τ_C far off the time delay Δt in comparison to Δt itself and it's relation to the relaxation time τ_R, we obtain with $\vartheta := \left(\tau_C - \Delta t\right)$

$$\mp\sqrt{\vartheta^2 - 2\Delta t^2} = \frac{\Delta t^2}{\tau_R} - \vartheta \quad \Rightarrow \quad 1 = \frac{2\vartheta\tau_R - \Delta t^2}{2\tau_R{}^2} \tag{14}$$

With $\Delta t^2 << \vartheta\tau_R$ the second term can be neglected and the remaining term yields $\tau_R = \vartheta = \left(\tau_C - \Delta t\right)$.

The *critical setting* is given by the condition $k/2 = \omega \to \rho/2\mu = \sqrt{\beta/\mu}$ and therewith $\tau_C = \Delta t(1+\sqrt{2})$ which leads to the optimal relaxation time constant:

$$\tau_R = 2/k = \frac{2\mu}{\rho} = \frac{\Delta t^2}{\tau_C - \Delta t} \tag{15}$$

Finally, the attempt to rule out deviations within shorter times (*weakly dampened*) invokes the oscillating solution where the overall relaxation time is:

$$\tau_R = 2/k = \frac{2\mu}{\rho} = \frac{\Delta t^2}{\tau_C - \Delta t} \tag{16}$$

Remark: As long as $\tau_R > 0$, the oscillations are dampened and finally run out. However, with $\tau_R > 0$ the exponential function changes its character to an escalating behavior. With $\tau_R = \Delta t^2/\left(\tau_C - \Delta t\right)$ this transition occurs at $\tau_C = \Delta t$ where the exponent changes sign.

Figure 2 shows the characteristic behavior of such a controlling structure over a wide range of controlling strength $k_C = 1/\tau_C$ for given unity time delay $\Delta t = 1$:

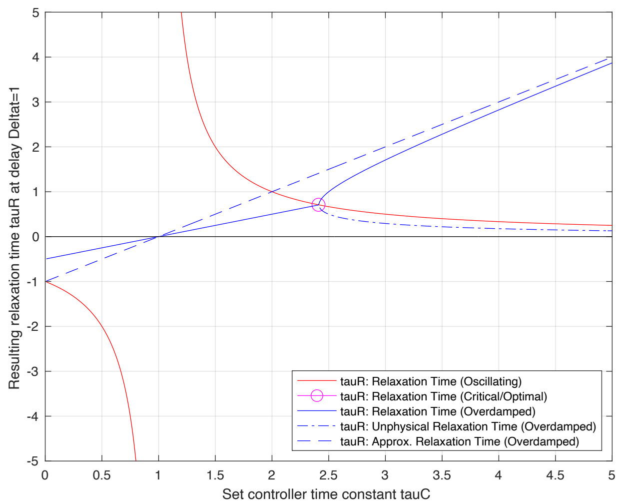

Figure 2. Theoretical development of relaxation time τ_R ranging from oscillating over the critical/optimal setting to the overdamped situation.

We clearly observe the critical setting as the optimal selection of controller time constants for obtaining the shortest possible governing time. Increasing given time constants τ_C, i.e. weaker governing strengths $k_C = 1/\tau_C$, lead to increasingly slower relaxation times. From the mathematically point of view, two branches are possible, where the correct one approaches a linear function with gradient 1, intersecting the abscissa at $\tau_C = \Delta t$.

Smaller time constants corresponding to applying a stronger controller (raise k_C) produces instable behavior performing increasingly oscillations, however damped and therefore still stabilizing after some time. Only if the controller time constant τ_C reaches the value of the given time delay Δt, the systems behavior changes from dampened to escalating oscillations with the change of sign.

6. Explicit Evaluation of Required Tolerance Margins

These theoretical results can easily be applied on a singular presumably linear production process. Let the rate of production, respectively the invested production resources be $R_{Prod} = dQ/dt$, leading to the product determined as quality Q_{Fin} after the production duration t_{Fin}.

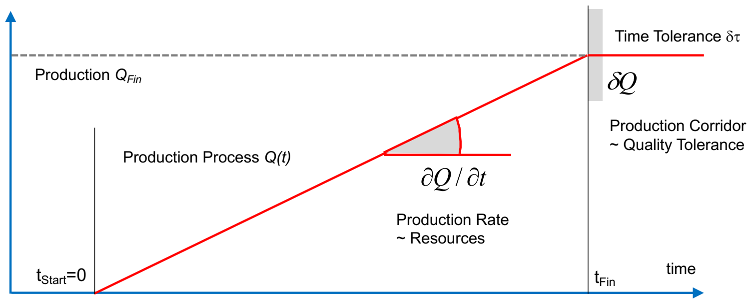

Figure 3. Linear process subjected to controlling.

Time Tolerance of a Controlled Linear Production Process

Using an implemented controlling process over the whole process where the delay Δt is given, the optimal controlling strength is about $k_C \simeq 0{,}41/\Delta t$ and the time constant $\tau_C \simeq 2{,}41\cdot\Delta t$. From this we derive the optimal relaxation time $\tau_R \simeq 0.707\cdot\Delta t$. However, since τ_R represents the time to bring a deviation down to $1/e$, we conclude a sensible required *time tolerance* to settle a possible deviation e.g. to 1% as: $\delta\tau = \tau_R \cdot \ln 0.01 \simeq 3{,}26\Delta t$, which is valid during the process and, thus, as well at the end of the process.

Quality Tolerance of a Controlled Linear Production Process

In order to derive a term helpful as quality tolerance we make use of [33] where we understand the meaning of the differential equation for an integral controller:

$$\frac{\partial Q_I}{\partial t} = [Q_I(t) - Q_{I0}(t)]k_I \tag{17}$$

as k_I corresponds to the percentage of the actual deviation of value Q_I that is invested efficiently in the production speed, thus in the resources ready exclusively for controlling purposes per time unit. Accordingly, we understand and name the ressources used for controlling purposes in this context $R_{Contr} = dQ_I/dt$.

Therein, we insert the known optimal controlling strength $k_C \simeq 0{,}41/\Delta t$ and transform to the equilibrium system $Q_{I0} = 0$: $R_{Contr} = 0{,}41\cdot\delta Q_{Contr}/\Delta t$. Rearranging gives a measure for the deviation δQ_{Contr} which can be mastered within the time tolerance $\delta\tau$ if the controlling ressources are given:

$$\delta Q_{Contr} \simeq 2{,}41\cdot\Delta t\cdot R_{Contr} \tag{18}$$

Dividing by the resources available for production $R_{Prod} = dQ/dt$ and integrating over the production time we obtain:

$$\delta Q_{Contr} = 2{,}41 \cdot \Delta t \cdot R_{Contr} \quad \Rightarrow \frac{\delta Q_{Contr}}{R_{Prod}} = 2{,}41 \cdot \Delta t \cdot \frac{R_{Contr}}{R_{Prod}} \quad \Rightarrow \frac{\delta Q_{Contr}}{Q_{Fin}} = 2{,}41 \cdot \frac{\Delta t}{t_{Fin}} \cdot \frac{R_{Contr}}{R_{Prod}} \tag{19}$$

Thus, we obtain the manageable relative deviation $\delta \tilde{Q}_{Contr} = \delta Q_{Contr} / Q_{Fin}$ requiring relative controlling ressources $\tilde{R}_{Contr} = R_{Contr} / R_{Prod}$ where the ratio is besides a factor of order 1 mainly determined by the time delay in comparison the process completion time.

$$\delta \tilde{Q}_{Contr} \simeq 2{,}41 \cdot \frac{\Delta t}{t_{Fin}} \cdot \tilde{R}_{Contr} \tag{20}$$

Remark: This value represents, what can be managed given the controlling ressources and the time tolerance derived from the controller during the process and, thus, at the end of the process as well.

In this context the time delay Δt represents the responsiveness of the controlling process. Thus, we replace Δt by the previously elaborated absolute time tolerance $\delta \tau = \tau_R \cdot \ln 0{,}01 \simeq 3{,}26 \Delta t$:

$$\frac{\delta Q_{Contr}}{Q_{Fin}} = 2{,}41 \cdot \frac{\Delta t}{t_{Fin}} \cdot \frac{R_{Contr}}{R_{Prod}} \Rightarrow \frac{\delta Q_{Contr}}{Q_{Fin}} = \frac{2{,}41}{3{,}26} \cdot \frac{\delta \tau}{t_{Fin}} \cdot \frac{R_{Contr}}{R_{Prod}} \Rightarrow \frac{\delta Q_{Contr}}{Q_{Fin}} = 0{,}74 \cdot \frac{\delta \tau}{t_{Fin}} \cdot \frac{R_{Contr}}{R_{Prod}} \tag{21}$$

Referring to a normalized process ($Q_{Fin} = 1, t_{Fin} = 1, R_{Prod} = 1$), we obtain the relation between manageable quality and time tolerance:

$$\delta \tilde{Q}_{Contr} \simeq 0{,}74 \cdot \delta \tilde{\tau} \cdot \tilde{R}_{Contr} \text{ and thus } \frac{\delta \tilde{Q}_{Contr}}{\delta \tilde{\tau}} \simeq 0{,}74 \cdot \tilde{R}_{Contr} \tag{22}$$

So far and very obviously we state the ratio of relative manageable quality to relative time tolerance given by the continuously available controlling ressources held ready. This relationship is widely valid, however, since the time tolerance $\delta \tilde{\tau}$ is principally predetermined (and limited) by the underlying controlling process, the resulting manageable quality $\delta \tilde{Q}_{Contr}$ is now tightly bound to $\tilde{R}_{Contr}$ and limited as well.

On this basis we estimate the general ability of controlling mechanisms to enforce a given and predetermined quality over the production process. Assuming given controlling resources $\tilde{R}_{Contr}$, quality deviation incidents up to $\delta \tilde{Q}_{Contr}$ can be compensated for if the time-tolerance $\delta \tilde{\tau}$ is allowed for. This is certainly true during the run of the process as well as at the end t_{Fin} where the controlling needs to continue operation using $\tilde{R}_{Contr}$ for another period of about $\delta \tilde{\tau}$. However, this limits the manageable quality deviation principally and all expected deviation exceeding this value need to go into a definite quality tolerance margin.

$$\delta \tilde{Q} = \left| \delta \tilde{Q}_{Dev} \right| - \left| \delta \tilde{Q}_{Contr} \right| = \left| \delta \tilde{Q}_{Dev} \right| - \left| 0{,}74 \cdot \tilde{R}_{Contr} \delta \tilde{\tau} \right| \tag{23}$$

7. Conclusion

Based on these theoretical considerations we state that any organizational structure can principally not be set up consistently and therefore will be in fundamental need of concepts of not only controlling overhead but also of tolerance. Any inconsistent system, i.e. not only far off the equilibrium state, but where the equilibrium state is only dynamically determined, cannot be stabilized totally.

If ruling mechanisms are at hand which principally allow inducing forces strong enough to compensate for inconsistencies, the system may become controllable. The optimal time constant of the balancing process as the central controlling parameter is widely independent of the degree of inconsistency or controlling force. The main parameter turns out to be the controlling delay, i.e. the reaction time of the controlling mechanism which cannot be assumed to vanish. Therewith, a principal minimum balancing time is given. At any attempt to reduce this by employing stronger controlling mechanisms, the system becomes increasingly unstable and leads to escalating behavior.

Thus, the rules for an acceptably controllable system are

- Clear definition of work-packages generated by probably strictly hierarchical structures.
- Understanding of the principally inherent inconsistency of this concept.
- Reducing complexity by avoiding long loops which increase the reaction time.

- Implementing local controlling structures, very close to all creative processes and independent of other structures (Complexity).
- Not only comparing quality to the pre-set plans but also to the capability of the production process and the suitability as a solution to the given problem.
- Determining the controlling strength according to the inherent controlling delay.
- And last and most importantly, introduce quantitatively sufficient tolerance on interfaces to deal with the unavoidable discrepancies of quality.

The consequences of this approach are proposed e.g. by concepts of lean management, however not exclusively. According to VDI 2553 [10] or the SCRUM manifest [8, 9] in particular the acceptance of inherent inconsistencies of organization and the short loop approach to tackle these is pointed out. After constructing the organizational system based on highly hierarchical structures with resulting inconsistent declarations, long communication paths and missing feed-back-loops, self-organizing teams with short paths and fast loops are implemented to solve discrepancies efficiently.

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