2022 American Control Conference (ACC)
Atlanta, USA, June 8-10, 2022

# Managerial Decision Making as an Application for Control Science and Engineering

Tariq Samad, Daniel Y. Abramovitch, Michael Lees, Iven Mareels, R. Russell Rhinehart, Francesco Cuzzola, Benny Grosman, Oleg Gusikhin, Esko Juuso, Bhagyesh V. Patil, Stefan Pickl

***Abstract*— The principles and methodology of control science and engineering are relevant beyond engineered systems to all dynamical systems. In this paper we discuss how control terminology and concepts can be interpreted in the context of decision-making by human managers, and the benefits that can accrue from the analogy. Examples of managerial decision making are presented in a control systems context. A selected review of earlier literature in the area is included. The connections of some popular business practices with control principles are reviewed. Points of differentiation, especially human-in-the-loop aspects of managerial control, are highlighted. Two examples, on return-on-investment dynamics and short interval control in process plant operation, are discussed. A number of control concepts are mapped to the management domain, revealing what we hope are useful insights for decision makers. This is the main paper for a tutorial session at the 2022 American Control Conference. An appendix is included that contains abstracts of the other papers and presentations in the session.**

## I. Introduction

Control scientists and engineers consider engineering systems as their target domains—the expectation is that if some research or development activity is successful it will help improve the performance, safety, reliability, cost-efficiency, and other aspects of human-engineered systems such as aircraft, automobiles, biomedical devices, buildings, and chemical plants. (Research in control science and engineering is also directed toward natural systems, in applications such as agriculture or biology.)

But the principles and concepts of control are of universal relevance to dynamical systems. Human organizations comprise one set of such systems that the controls community has not paid sufficient attention to. And, conversely, organizations suffer because of the lack of systems-oriented decision making.

T. Samad is with the University of Minnesota, Minneapolis, MN 55419, USA (tsamad@umn.edu)
D.Y. Abramovitch is with Agilent Technologies, Santa Clara, CA, USA
M. Lees is with Carlton & United Breweries, Yatala, Australia, and The University of Melbourne, Parkville, Australia
I. Mareels is with IBM Australia, Melbourne,,Australia
R.R. Rhinehart is with Oklahoma State University, OK, USA
F. Cuzzola is with PSI Software AG, Germany
B. Grosman is with Medtronic Diabetes, Northridge, CA, USA
O. Gusikhin is with Ford Motor Company, Dearborn, MI, USA
E. Juuso is with the University of Oulu, Finland
B.V. Patil is with the John Deere Technology Center, Pune, India
S. Pickl is with UniBw München, Germany

In this paper, we address how concepts, tools, and methodologies from control science and engineering can help bring rigor and rationality to human decision making in managerial contexts. This is the introductory paper for a tutorial session for ACC 2022 on the topic. The session includes additional papers and presentations; see the Appendix for abstracts for these.

## II. The Control Loop in Engineering and Management

Figure 1 shows a version of a typical feedback control loop. Mapping the diagram to a control system for any engineering application is straightforward, but the same diagram can also be mapped to managerial decision making. The two "interpretations" are compared in Table 1. In the figure and table, the terms used are from the control engineering lexicon; the last column suggests their extension to human organizations and managerial applications.

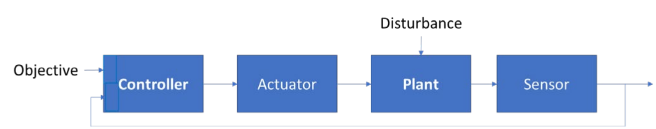


Figure 1. A representation of a control loop that can be applied to engineering or managerial applications

The interpretations of Table 1 identify several analogies and distinctions; these will be elaborated on as we delve into details.

Note that the illustration of Fig. 1 is simplified for both engineering and managerial applications. Both, but especially the latter, will exhibit considerable complexity if we look under the hood of the Plant or the Controller. To mention one example, in the management realm, high-level decision makers will have several groups under them, and each group will have subgroups too, with the hierarchy extending many levels. Thus, a Plant at one level will consist of closed-loop Controller/Plant subsystems, recursively. Interactions and couplings can exist among Plants and Controllers as well. Not only will managerial applications be hierarchical, but each is a multi-input, multi-output (MIMO) system.

We have also limited our focus to cooperative groups. In the business world, the competitive landscape is important to take into account for strategic decision making. Insights from game theory are relevant here and often alluded to, in both the popular and academic literature. In control terms,

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competition can be taken to imply that the Disturbance can be adversarial in nature—companies may make decisions specifically to disrupt competitors.

Table 1. Engineering and managerial interpretations of control technology terms

| *Nomenclature* | *Engineering Interpretation* | *Managerial Interpretation* |
|---|---|---|
| Plant | A natural or engineered system whose operation is to be managed (often also called a "process" or a "system"). | An organizational system whose operation is to be managed (often called a "team," "organization," "project," etc.). |
| Controller | An algorithm or collection of algorithms, usually implemented in software, that identifies actions to be taken on the Plant. | A decision-making agent, usually incorporating people and/or processes, that identifies actions to be taken on the Plant. |
| Disturbance | External influence on the Plant, usually from its immediate environment. | External influence on the Plant, from local or broader, including global and societal, phenomena. |
| Sensor | A device or system to measure relevant variables and parameters of the Plant or Disturbance. | A system, process, or methodology to collect data or information relevant to the Plant or Disturbance. |
| Actuator | A device or system that takes the output of the Controller as input and effects changes to the Plant. | A communication channel and/or process that takes the output of the Controller as input and effects changes to the Plant. |
| Model (not shown in Fig. 1) | A mathematical representation of the Plant (typically implemented in software) that is used in the design and/or operation of the Controller. | A representation of the Plant (usually in the minds of people but sometimes supplemented with software) that is used in the design and/or operation of the Controller. |
| Objective | The desired value of the Plant output or a functional criterion to be optimized for the Controller-Plant system, typically supplemented with operational constraints. | The desired output or outcome of the Plant or the Controller-Plant system, supplemented with operational constraints. |

Most of the examples that follow would be broadly classified as human-in-the-loop systems. However, even for these people-centric systems, there is utility in looking at what components can be automated, so as to lead to improved (faster and less biased) data collection, while allowing the humans to perform the higher-level decision functions. There is much historical precedence for this, including the gradual automation of anti-aircraft guns in World War II (Mindell, 2002).

## III. MANAGERIAL DECISION MAKING – EXAMPLES

Examples of managerial decision making that can be analyzed through a controls lens are all around us. We present a few here and attempt to translate the activities into control engineering terms. In each case, questions like the following need to be answered in order to facilitate the management-control analogy—we offer answers for the first example and leave the others as exercises for the motivated reader:

- What are the Objectives?
- What are the Controller outputs?
- What are the Plant outputs?
- What are the Disturbances?

The examples below suggest some general distinctions between control engineering and management decision-making, to be elaborated later.

### *A. Managing an Engineering Project*

You are a project manager for an engineering development—a new product for your company. You have received a product specification and your role is to provide direction to the engineering group you lead so that the product is delivered with acceptable quality, on time, and within budget—that is the Objective. You are the Controller in this scenario; the group you lead is the Plant. Your outputs can include allocations of resources to different subgroups or teams and providing objectives to these entities. The Plant output can be considered the current development status of the product. External factors such as weather-related or health-related disruptions to the work of the group would be examples of Disturbances.

### *B. Supply Chain Management*

You work in a manufacturing enterprise and your role is to ensure that your suppliers will deliver the required materials for your factory. As the Controller, it may be within your authority to effect changes to the inventory and warehouse operations of the factory, but your job also involves wielding influence outside and within the enterprise—e.g., on how your suppliers operate and on the manufacturing schedule. You, the Controller, may need to respond to a disruption in a portion of your supply chain by creating an alternative path (e.g., via a second source).

### *C. Teaching a Course or Directing a Graduate Program*

An instructor for a course is a manager, too, with the students as the Plant. The instructor's objectives include getting the students to learn the subject material and getting good evaluations from the students. Controller outputs include the syllabus the instructor prepares, the lectures delivered, responses to student questions, and graded assignments. The closed-loop outputs include those that are easily measurable: the proficiency of students on the homework and exams, and those that are hard to measure: the long-term retention of the class material by the students.

It's instructive also to take a step up from the above application and consider the case of a director of graduate studies for a program. Now the Plant includes the instructors teaching in the program and the curriculum. Other functions, such as recruitment and admissions, may also be included.

### *D. Managing a National Economy*

You are the Chair of the U.S. Federal Reserve, or an equivalent leader in another country. Your objective is to ensure a healthy economy, as measured by GDP growth, inflation, unemployment, and other factors. You are in charge of the monetary policy and your control actions can include setting interest rates and regulating money supply. But even public statements you make will influence the economy—these are also Controller actions. This is also an example of a system that has multiple inputs and multiple outputs but for which the controller can only affect a limited number of inputs and measure a limited set of outputs. We have seen that many "economic controllers" try to follow a planned path of regulated growth for economies. Too little growth leads to wage stagnation and lack of job prospects. Too much growth leads to inflation and supply shortages. Not being disciplined in sticking to a path leads to exaggerated economic boom and bust cycles, but agility is also required for reacting to Disturbances.

## IV. History of the Topic—Prior Work

Although there is not a vast literature dealing with organizational behavior, or management as part of the classical control theory and control practice literature, the connection has a long and persistent history.

Henri Fayol (1849-1925) (Fayol, 1916) in his book *Principles of Scientific Management* described management as consisting of (1) goal setting; (2) organizing resources; (3) command and communication; (4) coordinating hierarchies and functions; (5) control in the sense of measure, compare and correct (that is, implement feedback); and finally (6) forecasting or prediction. Fayol was trained as a mining engineer at the School of Mines, St.-Etienne, France, and well informed about the "control engineering" of the day (the governor). His approach to scientific management, informed by his training and experience, still underpins much of the contemporary approach in industrial management. To this date there is a rich literature dealing with, in particular, management control systems, e.g., (Anthony, Dearden, & Govindarajan, 2014), who discuss the merits of measurements and incentives to achieve key performance indicators, effective cost-reduction measures, or an objectives-key results framework. Equally, the management and behavioral science literature deals extensively with the notion of feedback, e.g., (Ramaprasad, 1983) attempting to provide a unified definition of feedback in management.

Norbert Wiener, in his treatise *The Human Use of Human Beings* (Wiener, 1950), clearly saw the behavior of humans (and animals, or nature) well within the scope of cybernetics and information theory. He saw as foundational to modern society that humans communicate—communication seen in a broad sense, not only considering verbal communication, but including everything we sense as part of the messages and signals relevant to communication. Also, he required consideration of the entire breadth of hierarchies in society and organizational units, levels of trust and mistrust, clarity of message, and capacity to understand and to mislead. According to Norbert Wiener, the key concepts to arrive at organization are information (as characterized by decreasing entropy) and feedback (to pursue a desired performance, or a purpose). At the very least, the very existence of a purpose requires one to avoid chaos, and in order to avoid (the inevitability of) chaos one needs to increase information or fight entropy. In Wiener's own words, "To live effectively is to live with adequate information." From a systems and control perspective, it is easy to see that we can apply this statement to the management of any organization or organized society, and indeed control itself (Nair, Evans, Mareels, & Moran, 2004). (Admittedly, the descriptive words "effectively" and "adequate" require much elucidation.) Therefore, we argue that it is important to reconsider management as being well within the scope of systems and control, and to reconsider, in the light of the advances made in control theory and technology, our ability to deal with complexity and uncertainty, and how control and feedback may contribute to management science and practice. Stafford Beer would approve (Beer, 1959). The proponents of systems science also push in that direction (Jackson, 1991).

Since its inception the International Federation of Automatic Control has had a technical Coordinating Committee dealing with social systems (Kopacek, Stapleton, & Dimirovski, 2017). The field is broad enough to include such socio-economic-political conundrums as international stability and peace! There is a different Coordinating Committee dealing with biology and ecology. These topics, as mathematical models are becoming mainstream in modern biology, can be seen as being well within reach of the classic paradigm of measure-model-control. Addressing social systems within the same paradigm remains daunting. Indeed, human behavior and organizational behavior are not readily captured through mathematical models, yet they are not beyond explanation either, and hence not beyond classical control theory.

## V. Successful Business Practices and How They Embody Control Concepts

In this section we take a view from the other side. Several management practices that have helped companies succeed can be analyzed from a control perspective, as illustrated here.

### A. Management by Wandering Around (MBWA) / Gemba

MBWA and Gemba are often traced to the founders of Hewlett-Packard in the U.S. and to Toyota in Japan, respectively. These practices involve managers at all levels walking or wandering (to add in randomness) around their domains to have direct interactions with the individuals doing the work (Packard, Kirby, & Lewis, 1995). Because the method is sparse and randomized, it bears similarities to compressive sensing (Candes & Wakin, 2008). Similar practices are also established within Lean and Six Sigma methodologies. The concept can be related to collocation of measurement and control—instead of information from the plant floor being filtered up to a central Controller through organizational layers for decision making, with decisions then filtered back down to the floor, the Controller (or part thereof) can both acquire unfiltered data and effect decisions at the point where the action must be taken. The practices can also be seen as substantially reducing measurement and actuation delays.

### B. Statistical Process Control (SPC)

SPC is well-established in the process industries as a methodology to distinguish underlying trends from noise (Vanli & Castillo, 2014). Overreaction to noise, often referred to as "tampering," will cause increased variability and wasted resources. In management, noise could be misinformation, incomplete information, misinterpretation of the process (erroneous mental models), etc. In management, tampering would also be perceived as capricious actions, leading to a loss of confidence in evaluations.

### *C. Six Sigma*

The intention behind the Six Sigma framework is to bring rigor and statistical thinking into business processes. A vast literature is available on the topic and numerous specializations have been developed, including Lean management and Design for Six Sigma (DFSS) (Chowdhury, 2002). A large set of tools have also been developed. An overarching concept is define – measure – analyze – improve – control (DMAIC), with apparent connections to control science and engineering. The “control” step in DMAIC includes continuous monitoring, thus incorporating the feedback element.

### *D. Objectives and Key Results (OKR)*

In today’s dynamic environment, a company’s success can depend on its organizational agility in the face of rapidly changing markets and limited predictability of the business horizon. The recently introduced OKR concept is a framework for organizational control loops that can address this need (Wodtke, 2016). It has been adopted by companies in tech and software industries (e.g., Intel, Google, Microsoft). OKR includes setting team/individual goals and methods for unbiased measurements of key performance indicators (KPIs). The intent is not to formalize a waterfall flow-down of company targets but to realize a control loop and feedback process that integrates KPI measurements, the company control variables represented by human decisions, and final company targets.

### *E. Minimum Viable Product (MVP)*

In today’s world, characterized as it is by volatility, uncertainty, complexity, and ambiguity (VUCA), long-term planning is increasingly untenable. Companies are pivoting their strategic thinking towards a paradigm of a minimum viable product. Following the MVP approach, companies launch a new product in the market with features that are basic, but sufficient to get the attention of consumers. The product is then iteratively improved based on consumer response. Technology and software companies have been at the forefront of this change—for example, distributing alpha or beta software releases to all users. We can relate important attributes of MPV with control science: a) the feedback element—taking feedback from consumers in early stages of design enables companies to position themselves for profitability; b) the iterative model building of adding complexity and features to the system with each iteration; and c) the adaptive management element—a learning-while-deploying concept that enables management to de-risk and optimize market share.

## VI. Some Points of Differentiation

The applications of control that the controls community is by-and-large focused on are to engineered systems: the development of Controllers for Plants such as aircraft, disk drives, robots, autonomous vehicles, units in factories, etc. The methodologies of the field have been developed with such applications in mind.

Managerial decision making is a qualitatively different kind of control application. Although related work has been done (as reviewed above), it remains underrepresented in control publications and conferences. Managerial decision making covers a wide space, and there is considerable variety in the applications involved—arguably more so than the variety in engineering control.

It is useful to identify some key areas in which engineering control and managerial control differ, and these areas can also be used to distinguish among different kinds of managerial control applications.

This is by no means a complete list. Other topics where differentiation is evident include multicriteria objectives, constraints, fault detection and correction, and game-theoretic strategies.

### *A. Models and Mental Models*

The quality of control we can achieve on an engineered system is substantially dependent on the accuracy of the mathematical model we can obtain of it. Much of the effort in control engineering is thus spent on modeling—using first-principles analysis and/or system identification. Similar models are rarely feasible for managerial systems. However, the general insight—how well we can control a system depends in good part on our knowledge of it—is still applicable. In the case of human decision makers, it is their *mental models* that can be considered an analog to the mathematical models of control engineering. That is, physical systems control methods can be used as a metaphor to guide managerial and business decisions (Abramovitch, 2022).

### *B. Measurements and Data*

Adequate sensors and associated instrumentation are considered a requirement for engineering applications. Adequate data is also recognized as necessary for developing models that will be used for control design or in control schemes like model predictive control. In some managerial applications, such as supply chain manufacturing, reasonable amounts of data are often available. In others, relevant data has traditionally been limited or absent. However, the increasing prevalence of “big data” and analytics groups and initiatives in organizations suggests that the importance of measurement and data is starting to be widely appreciated. Such groups can be seen as serving “sensor” and/or “estimation” functions in the managerial context. As with many physical control systems, there is often a lot of structure and many levels to the data, the measurement, and the decision and adjustment (control) activities.

### *C. First-principles Understanding*

In engineering, we expect to have some understanding of the physics (or other fundamental basis) of the phenomena in the Plant. In management, we may have intuitions about the phenomena but there can often be disagreements about basic matters. Even the polarity of an input-output causal link may be debated. Will increasing the corporate tax rate lead to higher or lower unemployment? Are drastic lockdowns during a pandemic (as in Australia) better or worse for a nation’s economy and health than loosening of restrictions (as in the U.S.)?

### D. Uncertainty

Control, and in particular feedback control, allows Plants to be managed despite uncertainty. In engineering systems, uncertainty arises through several sources: sensor noise or errors, imprecise knowledge about the Plant, and Disturbances. These are all relevant for managerial systems too. The level of uncertainty that most human decision makers contend with is substantially higher than for engineering Controllers—just the presence of people as elements of the Plant amplifies uncertainty. Furthermore, in control engineering we are used to characterizing uncertainty in quantifiable ways—this is often infeasible in management.

As stated by Daniel Kahneman, Nobel Laureate in Economic Sciences, "Inconsistent decision making is a huge hidden cost for many companies; by consistently leveraging scientific methods noise associated with irrelevant factors can be removed" (Kahneman, Rosenfield, Gandhi, & Blaser, 2016).

### E. Dynamics and Time Delays

The response times for most engineering control systems are much shorter than for most managerial systems—subsecond-to-minutes for the former, up to years or even decades for the latter. In both environments, a lack of understanding of time constants and time delays fundamentally hinder any control or decision process, and the longer time horizons of managerial systems further exacerbate the issue for them. Because of their shorter horizons, our engineering systems are far more sheltered, and their boundaries better delineated.

### F. Actuation and Action

Outputs of Controllers are informational signals. In engineering, these signals affect the Plant through physical mechanisms such as valves, switches, and motors. Because of equipment limitations, the input to the plant may not be exactly what the Controller commanded, but in most control applications this is not a major concern. In management, Controller outputs are often verbal or written messages. The lack of ambiguity in the signals of engineered systems can be contrasted with the imprecision and ambiguity (often intentional) of human language communications. What the Plant (e.g., the manager's staff) understands by the message may not be what the manager intended to convey—this can be seen as an example of entropy in the communication channel.

### G. The Scope of the Controller

The types of actions a managerial Controller can take are much broader than in the engineering case, extending well beyond the equivalent of adjusting valves, motors, or switches. Managerial edicts can result in major company reorganizations, disbanding or setting up of new groups, geographical expansion or retrenchment, mergers and acquisitions, and other actions that can dramatically alter the nature of the Plant.

### H. Multivariable Applications

Single-input-single-output (SISO) applications essentially do not exist in the world of management. All decisions involve multiple considerations and interactions must be considered. In engineered systems, this cross coupling is often unwanted and parasitic. When it is seen, minimizing the parasitic effects is often accomplished via modeling and decoupling control. A possible aid to decision making is simply in finding ways to measure and characterize the cross coupling of managerial decisions.

## VII. Management as Human-in-the-Loop Control

### A. Management of Human Organizations

Management comes from the contraction of the Latin word for "hand" (*manus*) and "doing" (*agere*). It was first used in the context of handling of horses, but soon adopted for all actions taken by humans in control of business. The very origin of the word "management" suggests that humans are central to management and that management is indeed a form of human-in-the-loop control.

Because of the reach and the size of organizations, we often see a hierarchical principle of management in place. A geometric progression—rulers over 10 that are themselves ruled by a ruler over 10, and so on—was described in Exodus in the Bible. It indicates that no organization needs more than 10 layers, i.e., a single world leader with fewer than 10 layers in the hierarchy can control the entire world (for the foreseeable future). This is not a pleasant idea. But it is hard to imagine that we could have an overarching principle or purpose with which to organize the entire world, with the possible exception of, simply, survival. On the other side, the small-world phenomenon, indicating that we can reach anyone on planet Earth through a chain of acquaintances less than seven long, suggests that hierarchical control is far from efficient in terms of getting consistent messages to everyone.

Given that humans are not totally predictable, and that their behavior is influenced by many factors beyond the control of a manager, it is clear that empathy and motivational ability are key attributes of good managers. Moreover, leadership is key. Peter Drucker's well-known aphorism, "Culture eats strategy for breakfast," indicates that the values and behavioral principles are key to the success of an organization. Unless values and purpose align, the intrinsic entropy in the organization will prevail, and the management strategy is doomed to fail.

### B. Cognitive Biases and Illusions of Humans and Their Impact on Managerial Decision Making

The extensive experiments by Kahneman and Tversky have enlightened us about the irrationality and illogic of human decision making in the face of uncertainty (Kahneman, 2013). People are poor at comprehending probabilities and display numerous biases and illusions that keep them from making logical decisions, especially when time for deliberation is at a premium. Loss aversion results in overweighting of potential negative outcomes relative to potential positive outcomes. Because of the endowment effect we overvalue something we own just because we own it. "The sunk-cost fallacy keeps people for too long in poor jobs, unhappy marriages, and unpromising research projects." Anchoring and priming influence our conclusions towards recent data or information we have been exposed to. (For suggestions on how to overcome our cognitive biases, see [Nesbitt, 2015]).

These limitations must be factored into management practices. In control parlance, it's a modeling problem. Our managerial Controller must be informed by appropriate models (which, in most cases, will be mental models) of the managerial Plant. Furthermore, for human-centric Plants, the models must incorporate the irrational and contingent nature of the people in the Plants. Models of humans in aggregations are also needed. In psychology and behavioral economics, models of human cognition have been developed, but these are not at the level of specificity and lack the dynamical elements needed for human-in-the-loop managerial control.

### C. *Limits of Human Predictability*

In management, human behavior is part of the key complexity we are dealing with. Given that human behavior is not predictable, and not completely determined by the organization, (personal life, different organizations, cliques an employee may belong to, health, etc., all effect behavior), we will never get all the measurements we need to observe the "state" of the plant. There are always going to be large unobservable parts in the organization, and hence a need to ensure that the unobservable influence is minimized.

## VIII. Example: Return-on-Investment Dynamics

As an example of the insights that control concepts can bring to business decision making, we discuss here some dynamical aspects of a key relationship: between R&D investment and profitability. As a result of time delays and feedback effects, this relationship is complex. If the dynamics are not appreciated, wrong inferences will be drawn and managerial decisions made and evaluated incorrectly.

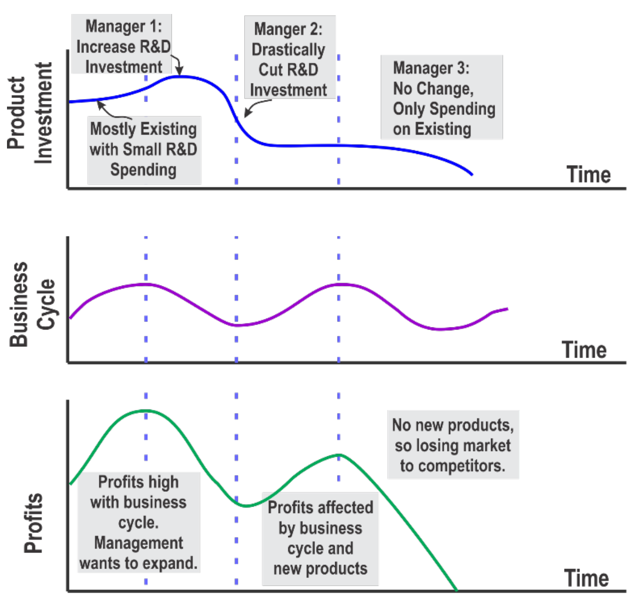


Figure 2. Product investment, business cycles, and profits aligned over time. The time lag between observation and the effects of positive action, can lead to bad outcomes.

In Figure 2, we see a hypothetical example of how business cycles and the timing of management decisions can turn good policies into bad ones. The middle plot shows the business cycle, which is understood to be oscillatory, but not exactly periodic. It is usually affected by many factors outside of any particular business.

When profits are high, upper management tends to support more investment. That means taking the baseline investment needed to turn out current products and possibly investing in new products via R&D spending. In the top plot, Manager 1 does the right thing and expands investment in R&D. In general, R&D spending can take several years to show its positive effects through new product sales. In the interim, if the business cycle takes a downturn, profits fall. The judgment of Manager 1 is questioned, and she is replaced by Manager 2.

Manager 2 is given the mandate to cut costs in order to increase profitability in the near term. R&D investment is a frequent target in such situations. The projects started by Manager 1 are canceled before they can have a positive impact on profits, but cost-cutting improves profits. The business cycle recovers as well. Manager 2 gets the accolades for the turnaround and is promoted to a higher-level role in some other part of the company.

Manager 3 is handed a profitable concern, but one with deflated R&D and no new products in the pipeline. Soon, the long-term effects of gutting R&D spending come home to roost. Competitors have caught up with and perhaps exceeded the legacy products from the division, but there are no new products available to allow market share to be sustained. Market share and profits drop and there is not much left of the business to recover. Manager 3 is associated with the failure of the business.

Thus, the best manager was removed, the worst manager promoted, and the wrong manager blamed for the final failure. A management understanding of the dynamics of business cycles, R&D investments, and profits (in particular, that there is an inverse-response relationship between R&D investment and profits) would alleviate such scenarios.

## IX. Example: Short Interval Control in the Process Industry

Many contemporary process industries are automated to some extent, but still rely on human operators for many aspects of plant operation. There are typically many important key performance indicators (KPIs) that need to be monitored and controlled. Hence the operator is a key component in numerous human-in-the-loop control applications. Despite the availability of real-time data and a range of analysis tools, the consistency and performance of human-in-the-loop (HitL) applications can vary markedly.

Short interval control (SIC) is a tool that has been developed in an effort to drive consistency and to reduce variability in this type of HitL control application (Vorne Industries, 2011). SIC was used by SABMiller, who were at one stage the second largest brewer in the world (employing around 69,000 people and operating in 80 countries worldwide). SIC was a key part of their global manufacturing excellence program, *The Manufacturing Way*, and was implemented in most lines and departments of its breweries worldwide. The 2016 acquisition of SABMiller by ABInBev (the world's largest brewer) and the subsequent divestiture of a number of individual divisions has spread the use of SIC across an even greater number of plants and companies worldwide. While SIC is a simple application of control science to management decision making, the scale of implementation across the globe is testament to its effectiveness and substantiates its industry relevance.

SIC is a tool for improving and standardizing the performance of time-varying HitL control applications (Lees, 2015) and is particularly effective for applications such as:

- Achieving an expected production output (or trajectory) from a manufacturing plant over a period of time
- Maintaining KPIs such as: product quality, yield, and utilities consumption
- Minimizing (containing) a production defect rate

The SIC concept is hierarchical as illustrated in Fig. 3.

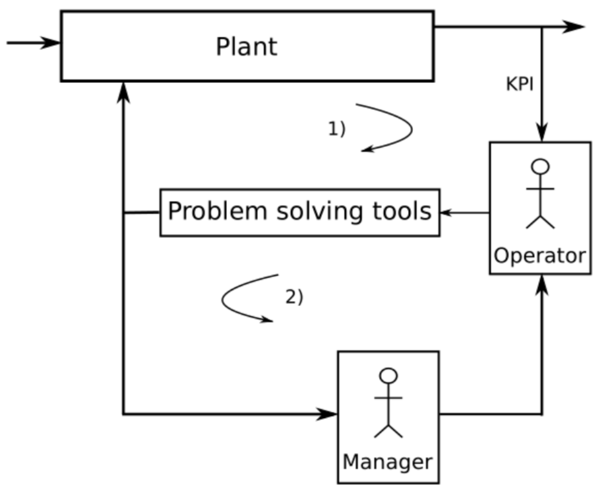


Figure 3. SIC feedback loops: 1) Plant operator monitoring and correcting issues with the plant/KPIs; 2) Manager monitoring and correcting issues with the operator's performance

### *A. SIC Primary Loop: Operator*

The primary loop (driven by the operator) can be described as a number of steps:

1. Monitoring: Human operator monitors the KPI at a predetermined frequency (ranging from every 15 minutes to an hour depending on the KPI) against the pre-determined control limits for that KPI.

2. Ownership of the value: The operator records the monitored value on a specifically designed whiteboard template or on a time-series plot. A red or green color is used to convey whether the value is good or bad. The process of the operator handwriting the values is considered to increase the person's sense of ownership of the value and their responsibility for maintaining control of the process/KPI (automation of the informatics and reporting is considered to be counter-productive).

3. Evaluation: In the event of a bad value, the operator checks to see whether it has met the threshold to trigger formal problem solving (an example trigger may be exceeding the upper control limit for three values in a row).

4. Problem solving: The operator performs the predetermined problem-solving process to determine the root cause of the issue. Formal techniques such as "5 Whys" (Murugaiah, Jebaraj Benjamin, Srikamaladevi Marathamuthu, & Muthaiyah, 2010) are used.

5. Resolve problem: The operator either resolves the problem directly or escalates it to others as required (e.g., trades or management).

### *B. SIC Secondary Loop: Manager*

SIC also includes a manager layer of regulatory control of the operator's performance.

The manager reviews the operator's use of SIC. The frequency of review would typically depend on the line and the value of the KPI but could range from multiple times per shift to once per day. The review frequency is polled (not event-driven) to ensure that focus is maintained; manager control by exception does not always deliver an equivalent quality of result. One of the intents of SIC is to force quality of control by removing the optional aspects (to attention and effort). Managerial supervision of SIC by exception could potentially result in the re-introduction of these qualities, undermining the intent.

The review process includes:

1. Confirmation that a) values have been monitored and recorded at the required frequency, and b) problem solving has been done for each trigger. This step of the process evaluates the quality of problem solving to confirm that it has been done correctly and confirms that the root cause has been detected and that problem resolution has occurred.

2. Escalation: Assist with escalation if required (especially where solutions require funding).

3. Feedback: Provide feedback to the operator regarding their use of SIC.

### *C. Benefits of SIC*

How is SIC any different to regular use of historical trending tools?

The tightly managed feedback loop ensures that SIC is completed at the required frequency and that root cause identification and resolution have been completed each and every time. The manager's feedback loop ensures that the use of SIC is not optional and the required quality of outcome has been obtained. Good outcomes can be achieved through the regular use of historical trending tools. However, without SIC the use of the correct tools at the correct time (and the consistent and correct use of root cause analysis) are typically optional. By emulating characteristics of automatic control loops, SIC provides greater consistency across the variability of different operators, supervisors, and time of day.

### *D. Opportunities to Improve SIC*

While SIC is quite effective (most definitely in comparison to its absence) it does have scope for improvement. One of its limitations is that it is a time-intensive practice (which is counter to the intent of Lean). There are opportunities to improve it further with a deeper application of control science principles. Example opportunities include: a more scientific basis for determining monitoring intervals (based on the nature of each specific KPI) and for determining the frequency of manager/supervisor polled monitoring.

## X. Three Approaches for Control Applications to Managerial Decision Making

We began this paper with the insight that engineering control techniques and methodologies have much to contribute to decision making in organizations. Here we outline three different approaches to that end. These approaches can be applied synergistically. Different facets of an organization or its decision-making functions could be well suited for one or the other of the approaches, and, with more data and digitalization, applications could transition from concepts and guidelines to algorithms and automation.

### A. *Approach 1: Control as Usual*

A "control as usual" methodology can be applied directly to business applications. For some managerial applications, the capabilities for modeling, sensing/measurement, predictability, etc., can be conducive to control engineering methodologies. See (Sterman, 2000) for numerous examples.

### B. *Approach 2: Control Principles as Guidelines*

Fundamental control principles can serve as a guide for managerial decision making. Most managerial applications will not permit Approach 1. However, in these cases, concepts such as feedback, modeling, optimization, estimation, disturbances, etc., can provide "insights" for managers that can be useful for their decision making (Samad, 2020)(Abramovitch, 2022).

### C. *Approach 3: Cross-disciplinary Collaborations*

Cross-disciplinary collaborations can be developed for control applications in decision making. This approach falls in-between the above two and represents opportunities for the controls community to leverage developments in other fields. Systems thinking is a particular case in point. The recognition that businesses are dynamical systems and that control systems ideas can be fruitfully applied can be traced to the work of Jay Forrester on systems dynamics (System Dynamics Society, n.d.). Systems thinking traces its origins to systems dynamics and hence to control systems as well, and can be seen as providing approaches for qualitatively modeling human-centric control loops for managerial and societal applications (Senge, 2006).

Another example is fuzzy systems. The use of fuzzy sets and fuzzy relations allows a mapping between linguistic expressions and the numerical realm and thus can help bridge the gap between qualitative reasoning and quantitative support (Juuso, 2020). Fuzzy logic representation can provide a pathway through which a manager's tacit knowledge (in this context, his internal decision-making algorithm) can be externalized. In other words, fuzzy methods, providing a way of implementing known, intuitive control laws into a numeric or computer format (Abramovitch, 1994), may be ideally suited to bridge the certainty of control principles with the uncertainty of mental models. Once externalized, knowledge is then accessible to others and becomes available for analysis, consistency checking, optimization, replication (via training material for other managers), embedding into algorithms, or understanding it to the extent that it can then be modified based on improvements from the quantitative realm.

## XI. Opportunities: Applying Control Concepts to Management

### A. *Clarity of Nomenclature*

In casual discourse, as well as in managerial communications, both written and verbal, words and phrases are used to convey information that influences decisions made, with societal and economic impact. These terms are often not well-defined, exposing opportunities for confusion, miscommunication, and poor decisions. The rigor of control science and engineering provides an alternative. To take one example, in control engineering we demarcate model uncertainty, disturbances, and sensor noise, all of which may elsewhere be lumped together under terms like uncertainty or noise. The distinctions are useful since the origin of each source of uncertainty is different. Model mismatch can arise from incomplete data or a priori information. Disturbances are external effects that are hard to model, and often unmeasurable. Noise is associated in particular with sensors and indeed with all forms of data collection; it may often be truly random, but biases are also possible. Another example where well-defined terms from control can help with managerial decision making is outputs versus states (see below).

### B. *Outputs Versus States*

The difference between Plant outputs—the externally observed and measurable signals—and the state variables of the Plant—the key variables in the cause-and-effect phenomena determining the behavior of the Plant—is an elementary lesson in control systems, and a vast literature on estimators and observers is available to derive state variables from the measurements. This distinction is crucial for all dynamical systems, and managerial systems are no exception. An exclusive focus on key performance indicators, for example, can blind managers to underlying factors that are hard to measure but nonetheless drive performance and KPIs. Developing a model of managerial inner workings that can be verified with measured data may give significant benefits in avoiding these dangers, and adhering to the fundamental principles of feedback may help guide such modeling.

### C. *Sampling Rate Versus System Time Constant*

How often should measurements from a Plant be taken and processed? That the sampling rate must relate to the dynamics of the Plant is obvious to anyone versed in control, but not necessarily to others. There are numerous analogs in the management world. How often should performance evaluations be done? How frequently should strategic planning exercises be undertaken? What about project meetings? When are agile and scrum practices to be recommended? The answers to such questions hinge on the time-scale over which the Plant evolves and the complexity of the dynamics.

### D. *Effect of Delays on Performance and Stability*

Delays in a control system can arise from multiple sources: actuators, the Plant itself, sensors, communication channels. Regardless, the presence of delays severely impacts closed-loop performance. In control engineering, the importance of minimizing delays when possible, and of incorporating delay compensation in the Controller calculation when not, is well-established. Managerial decision making is replete with long delays as well, and control concepts for delayed systems can beneficially be applied here.

### *E. Robustness-Performance Tradeoff*

Other things being equal, there is an inherent tradeoff between the performance that can be achieved in a controlled system and its robustness to uncertainty. High performance is achieved at the cost of lower resilience to noise, model mismatch, and disturbances, and if we insist on high levels of robustness, performance under nominal conditions can suffer. Similar considerations apply in management but are not generally appreciated.

### *F. Plant-Model Mismatch*

On a related note, and as mentioned earlier, all advanced control is model-based control and the quality of control achieved in an engineering application is intimately dependent on model accuracy. For managerial decision making, the development of accurate mathematical models will generally not be feasible. Instead, human managers rely on their mental models for decision making. The same dependency applies, however: Quality of decision making is dependent on the quality of mental model. Knowing how accurate one's mental model is, and improving that model based on observations, are therefore crucial. The less the manager knows about the Plant under her control, the less aggressive her decisions should be, and expectations of high performance need to be appropriately reduced.

## XII. Conclusions

The benefits of managerial decision making, once informed by the principles of control science and engineering, will accrue not only to corporations. Humanity is facing an existential threat. Development of better engineering systems (e.g., more reliable, lower-cost, fossil-free energy systems) is important for mitigating and adapting to climate change. But it is human decision making that's going to determine what kind of planet the next generation will inherit. Similar considerations apply for other planetary-scale challenges: global conflicts, food and water supply, world health, . . . We need leaders, managers, and citizens to make good control decisions.

Every person is a manager in some way or another. If nothing else, we all have to manage our time and our interactions with others—families and friends, professional colleagues, our communities. A better understanding of control principles would be beneficial to all.

## Appendix

We include below five abstracts for presentations that will accompany this main paper in the tutorial session. Papers for the conference proceedings have also been prepared for two of the presentations; references to these are also included.

### *A. Network Control System Applications for Manager Decision-Making*

*Author:* Michael Lees, Control & Automation Manager, Carlton & United Breweries, Australia, michael.lees@cub.com.au

*Abstract:* Many categories of manager decision-making (human organizations, environmental systems, supply chains) are in some way or another related to systems. However, system dynamics do not always lend themselves well to superficial, or intuitive, interpretation. This can inadvertently result in suboptimal managerial decision making. The application of control science concepts for guiding managerial decision making has the potential to improve results.

The contemporary manager is typically resource-constrained and time-stressed. Control-science-based decision-making guidance that does not accommodate the reality of the manager's time constraints may have limited affect in practice. A manager's attention-scheduling behavior is more analogous to that of a networked control system (NCS) than to that of a singularly focused control loop. There is an opportunity to apply NCS aspects of control science to identify the minimum attention/frequency requirements of key decision-making realms.

This paper acknowledges the time-poor reality of the contemporary manager. It considers how learnings from NCS theory can be applied to add resilience and efficiency to control-science-inspired improvements to manager decision making.

Just as regulatory control systems don't perform well when subjected to unexpected network or input/output delays, the application of control theory concepts to manager decision-making will be challenged if the time-poor aspects of the manager are not catered for.

For more information see (Lees, 2022).

### *B. Feedback Entropy—A Conceptual Framework for Management*

*Author*: Iven Mareels, Director, IBM Australia, imareels@au1.ibm.com

*Abstract*: The notion of feedback entropy is fundamental in control in that it describes when feedback is essential, and what information rate is required to maintain stability. Moreover, it is independent of how the feedback is implemented. In a nutshell, stability can only be achieved when the information loop seen as a communication channel is capable of transmitting more information (bits / sec) than the (feedback) entropy generated in the loop.

In a control system context, unstable systems generate entropy (in the linear system case Bode estimated this rate precisely), but also chaotic processes generate entropy, and the unpredictable effect of disturbances generate entropy. Traditionally entropy is considered in a stochastic framework, but a set-theoretic, deterministic approach is equally feasible.

In the light of these observations, this presentation revisits Norbert Wiener's quote, "To live purposefully, means to live

with adequate information," in consideration of the management of an enterprise, where the purpose is to deliver the enterprise's strategy and vision (whilst the market approves and provides the money signals to continue).

In management systems, where many people work in unison to deliver on the strategy and vision (for a personal benefit derived from the enterprise), uncertainty stems from both external, unpredictable influences (competition, regulatory actions, market effects, human resources, Covid-19, supply chain disasters), as well as internal human behavior effects such as poor communication through hierarchies, misalignment of management and personal objectives/ambitions, ineffective measurements, and inherent human biases in decision making. The model of "total entropy management" previously discussed in the economic management literature, can be re-interpreted and refined using the notion of feedback entropy. Attention is paid to how one measures "purpose" and "adequate," the two key words in Wiener's statement.

### C. *Business Performance Management and Control Systems*

*Author:* Francesco Alessandro Cuzzola, PSI Software AG, Germany, francescoalessandro.cuzzola@polimi.it

*Abstract:* A key question for every manager in industry is Why do my customers come to me? (And will they continue to come to me in the future?) This is a complex question, and it is strictly correlated with governance/control capabilities of the company along with the characteristics of the specific field under consideration. Additionally, today's world is fast-changing and, given global communication and transportation delays, localization benefits can offset the globalization tendency—provided that the necessary product has a high level of customization and must be supplied to the customer quickly.

This is the starting point for explaining the reason why today's companies are striving to implement a Performance Measurement and Control System (PMCS), i.e., a tool to assist managers in decision making that allows them to manage the company adaptively. A first objective of a PMCS is to systematically collect data in order to be able to assess how effective the company has been in satisfying customer needs and how efficient the company has been in resource usage for achieving the desired targets. The second objective is the possibility to assist in implementing changes in the company organization taking into account several control variables that influence the performance of the company networks. More precisely, we might consider two different control-variable dimensions: the technical control dimension (i.e., the set of all technical production procedures and the set of methods for explicit knowledge management) and the social control dimension (i.e., the capability of communicating vision and value inside and outside the company).

As outlined above, this presentation will show how these business imperatives can be effectively addressed with a control engineering approach.

### D. *Prescriptive Analytics and Control Towers: A New Dimension of Managerial Decision Making in the Age of Reinforcement and Machine Learning*

*Author*: Stefan Pickl, Director COMTESSA, UniBw München, stefan.pickl@unibw.de

*Abstract*: Managerial Decision Making will be influenced in the future by certain developments of AI-based expert systems, machine learning techniques as well as different reinforcement learning approaches. These approaches extend the classical C2-network approaches as well as standard expert systems in the sense of Norbert Wiener and lead to a new concept of intelligent control towers.

These control towers are characterized by "prescriptive analytics" facilities which will be one of the main components of future managerial decision concepts. The concept combines online algorithmic techniques with new domains of communication structures in order to control a complex system via comfortable managerial dashboards. Prescriptive analytics could be considered as an example how managerial decision making could be seen as a further application for control science and engineering.

### E. *Using Feedback Control Principles as Guiding Metaphors for Business Processes*

*Author*: Daniel Y. Abramovitch, System Architect, Agilent Technologies, daniel_abramovitch@agilent.com

*Abstract:* This paper asks: how do we apply the fundamental principles of feedback in physical systems to business processes? This is a tempting idea because feedback is clearly present in business/decision processes, but as in the case of feedback of biological systems, getting beyond the qualitative and phenomenological descriptions to models with structure for which parameters can be determined from measurements is difficult.

In this context, what can feedback principles, so often based on rigid mathematical analysis, provide to such systems for which any mathematical rigor is hard to find? Our approach in this section will be inspired by the words of Captain Barbosa in *Pirates of the Caribbean*, as to think of fundamental feedback principles as guidelines, rather than actual rules. That being said, we believe those guidelines provide a rich source of correction for business processes. In the end our feedback-fundamentals-inspired guidelines may not guarantee us always-correct decisions, but they can keep us away from practices we would never try in engineering systems.

For more information, see (Abramovitch, 2022).

## Acknowledgment

The authors of this paper are members of a task force on "Control Concept for Managerial Decision Making" of the IFAC Industry Committee (https://www.ifac-control.org/areas/industry-committee). Other members of the task force also contributed to discussions relevant to the topic of this paper: Lane Desborough and Zdzislaw Kowalczuk.

## References


Abramovitch, D. Y. (1994). Some Crisp Thoughts on Fuzzy Logics. *Proc. American Control Conf.* Baltimore, U.S.A.

Abramovitch, D. Y. (2022). Using Feedback Control Principles as Guiding Metaphors for Business. *Proc. American Control Conf.* Atlanta, U.S.A.

Anthony, R. N., Dearden, J., & Govindarajan, V. (2014). *Management Control Systems, 12th ed.* McGraw-Hill/Homewood.

Beer, S. (1959). *Cybernetics and Management*. John WIley & Sons.

Candes, E. J., & Wakin, M. B. (2008). An Introduction To Compressive Sampling. *IEEE Signal Processing Magazine*, *25*(2), 21–30. https://doi.org/10.1109/MSP.2007.914731

Chowdhury, S. (2002). *Design for Six Sigma: The Revolutionary Process for Achieving Extraordinary Profits*. Dearborn Trade Publishing.

Fayol, H. (1916). *Administration industrielle et générale*.

Jackson, M. C. (1991). *Systems Methodology for the Management Sciences*. Plenum Press.

Juuso, E. K. (2020). Expertise and Uncertainty Processing with Nonlinear Scaling and Fuzzy Systems for Automation. *Open Engineering*, *10*(1), 712–720. https://doi.org/10.1515/eng-2020-0080

Kahneman, D. (2013). *Thinking Fast and Slow*. Farrar, Straus and Giroux.

Kahneman, D., Rosenfield, A. M., Gandhi, L., & Blaser, T. (2016). Noise: How to Overcome the High, Hidden Cost of Inconsistent Decision Making. *Harvard Business Review*.

Kopacek, P., Stapleton, L., & Dimirovski, M. (2017). FROM SWISS TO TECIS AND BEYOND. *IFAC-PapersOnLine*, *50*(1), 6361–6366. https://doi.org/10.1016/j.ifacol.2017.08.1022

Lees, M. (2015). The Global Enterprise and Process Control. *5th Australian Control Conference*.

Lees, M. (2022). Network Control System Applications for Manager Decision-Making. *Proc. American Control Conf.* Atlanta, U.S.A.

Mindell, D. A. (2002). *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*. Johns Hopkins University Press.

Murugaiah, U., Jebaraj Benjamin, S., Srikamaladevi Marathamuthu, M., & Muthaiyah, S. (2010). Scrap loss reduction using the 5-whys analysis. *International Journal of Quality & Reliability Management*, *27*(5), 527–540. https://doi.org/10.1108/02656711011043517

Nair, G. N., Evans, R. J., Mareels, I. M. Y., & Moran, W. (2004). Topological Feedback Entropy and Nonlinear Stabilization. *IEEE Transactions on Automatic Control*, *49*(9), 1585–1597. https://doi.org/10.1109/TAC.2004.834105

Nesbitt, R. E. (2015). *Mindware: Tools for Smart Thinking*.

Packard, D., Kirby, D., & Lewis, K. (1995). *The HP Way: How Bill Hewlett and I Built Our Company*. Collins.

Ramaprasad, A. (1983). On the definition of feedback. *Behavioral Science*, *28*(1), 4–13. https://doi.org/10.1002/bs.3830280103

Samad, T. (2020). Control Systems-Concepts and Insights for Managerial Decision Making. *2020 IEEE 10th International Conference on Intelligent Systems, IS 2020 - Proceedings*. https://doi.org/10.1109/IS48319.2020.9199940

Senge, P. (2006). *The Fifth Discipline*. Currency.

Sterman, J. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill Education.

System Dynamics Society. (n.d.). Origin of System Dynamics. Retrieved July 25, 2020, from https://www.systemdynamics.org/origin-of-system-dynamics

Vanli, O. A., & Castillo, E. Del. (2014). Statistical Process Control in Manufacturing. In J. Baillieul & T. Samad (Eds.), *Encyclopedia of Systems and Control* (pp. 1–7). https://doi.org/10.1007/978-1-4471-5102-9_258-1

Vorne Industries. (2011). Short Interval Control (SIC). Retrieved from LeanProduction website: https://www.leanproduction.com/short-interval-control/

Wiener, N. (1950). *On the Human Use of Human Beings: Cybernetics and Society*. Houghton Mifflin.

Wodtke, C. (2016). *Introduction to OKRs*. O'Reilly Media.