Heuristic Problems in Automation and Control Design: What Can Be Learnt from TRIZ?

Chechurin Leonid, Berdonosov Victor, Yakovis Leonid, Kaliteevskii Vasilii

DOI: 10.1007/978-3-319-78075-7_4

Please cite the publication as follows:

Chechurin L., Berdonosov V., Yakovis L., Kaliteevskii V. (2019) Heuristic Problems in Automation and Control Design: What Can Be Learnt from TRIZ? In: Chechurin L., Collan M. (eds) Advances in Systematic Creativity. Palgrave Macmillan, Cham DOI: 10.1007/978-3-319-78075-7_4

Heuristic problems in automation and control design: what can be learnt from TRIZ?

Leonid Chechurin (a), Victor Berdonosov (b), Leonid Yakovis (c), Vasilii Kaliteevskii (a)

a. Lappeenranta University of Technology, Finland

b. Komsomolsk-na-Amure State Technical University, Russia

c. St. Petersburg State Polytechnical University, Russia

Abstract. The chapter starts the discussion from the history of automatic control review. It shows how this field of engineering evolved from pure heuristic designs (inventions) to the home court of applied mathematics. Thanking to this evolution, modern automatic control is able to formally provide standard out of shell solutions to any object or technology. At the same time this standardization can be a cause for professional thinking inertia. The latter may be a reason to miss possible automation ideas when they are out of the "sensor-controller-drive" box. The chapter speculates on how the principle of Ideal Final Result (and accompanying TRIZ tools such as trimming and resources search procedures) can enlarge the toolkit of automation engineers. It also discuss how ideality principle can be interpreted in terms of plant modification. Three examples illustrate the application of ideality principle for automation design. Several inventive ideas in hydraulic power steering system design are analyzed in detail in the first example. The second example demonstrates how mathematical modelling (in contrast to any TRIZ modeling techniques) can be more productive in inventive idea generation. The third example presents detail analysis of heuristic part of concurrent (parallel) plant and control design in process control.

1. Introduction

There are two distinct periods in the evolution of the research and application field called automation and control theory. The era of ancient inventions left us the descriptions and drawings of machines and mechanisms that empowered human beings. And even more, completely replaced the human intervention, making something happening itself, like in the nature. The gate opening mechanism by Heron of Alexandria (10 –70 AD) could be an example of the first drive design. The rise of needs and engineering ambitions evolved into the problem of the automatic governing of a device output. The latter has been referred in the modern terminology as tracking or error stabilization. There are two known remarkable inventions of early Discovery Era that illustrate typical approach to self-governing. One is found in the drawings of Leonardo and depicts self-rotating roasting jack. Its rotation rate follows the fire intensity thanking to the propeller in the chimney. Another seems to be the first thermostat by C. Drebbel's (1624), where the incubator's vents opening follows the temperature in the incubator thanking to a mercury piston. An unknown ingenious Dutch mind developed a mechanism that controlled the gap of windmill's running stone in respect to the speed of wind. Most probably, J. Watt simply adopted the idea to the steam turbine rotational rate stabilization in his famous patent of 1788.

The scaling of steam machines revealed the cases of instable rotation of some turbines with Watt's governor. The invention yielded obviously new phenomena and this phenomena had to be scientifically explained. J. Maxwell and A. Vyshnegradsky independently modelled the closed loop steam turbine behavior and provided the safe governor's parameters set. This analysis opened a new era in control system design: the pure inventive concept of the self-governing device became supported by mathematical performance analysis and optimization. One of the brightest examples was famous feedback vacuum tube amplifier invention filed by H. Black (1932) and provided with the stability analysis by his colleague H.Nyquist. These two mathematical treatments of feedback system stability are typically referred as the beginning of control theory. Any theory is to turn inventing into systematic routine sooner or later. And it basically happened by the mid of XX century, when the synonym of control and automation became the mathematical model based feedback design and optimization. The automatic control design arrived at the following general algorithm:

1. Choose the model for the Object;
2. Identify its parameters;
3. Define the control goals, model them;
4. Design a Controller;
5. Optimize its parameters;
6. Implement in hardware.

Indeed, that is a great achievement of the control theory. This formalization almost excluded the heuristic (and therefore unpredictable) component from the automation design process. And at the same time, nothing comes without drawbacks and the standardization is not an exclusion. We are going to highlight various difficulties of “classic automation approach”.

1. Control and automation are expensive. It requires measurements (sensors), controllers and drives plus automation engineer work.
2. The required controller is not always feasible. Or it is feasible, but in theory only. Or it is feasible at the expense of big power losses.
3. The complexity of the closed-loop system is equal to the complexity of the plant plus the complexity of the controller. More elements in general would mean higher failure probability.
4. Automation/control engineer starts her/his project when the object of control has already been designed. It is assumed that the object of control cannot be changed. It is the starting point for formal control design, although not so often case in reality.

And, at more generic level, we want to change the nature, the existing way of doing things, to design a useful machine (not just understand and explain the nature, like in most physics) and/but we want the designed device to work itself, like in the nature.

The main idea of the study is to provide a strategy of automation, that might add inventive ideas to the standard model based control designs. The inventive part of the design is inspired by TRIZ (Ideal final result, resource analysis).

If we use the concept of IFR at the macro-level of automation system design we have to setpoint the situation when the there is no need for control at all, the object operates itself the way we need. What if we modify the object to be controlled in such a way that the control either not needed or becomes much simpler?

The approach is illustrated by three case studies. One presents the analysis of hydraulic booster control system design analysis, where the inventive redesign dismissed the necessity to introduce the feedback system. The inventive part of redesign is inspired by IFR and contradiction elimination models. The second example is the treatment of classical sway stabilization problem. The systematic generating of conceptual ideas is based on mathematical model of the object. The third example is the analysis of technology process control design problem. Standard automation design and inventive object redesign give an idea for hybrid approach and its mathematical optimization.

2. Case Study 1: Hydraulic Power Steering System

Let us consider a hydraulic power assisted steering (HPAS) mechanism as an example. Power steering is designed to make the driving safer through assisting the driver in guiding the car in normal situations (parking, highway driving, etc.) and in emergency (front tire rupture) [1, 2]. The primary power steering function is to reduce forces exerted on the steering wheel and at the same time reduce the steering ratio. Other functions are:

1. To reduce the driver fatigue;
2. To improve the car maneuverability;
3. To assist better “road feeling” for the driver.

2.1 Rack-and-pinion steering without hydraulic power

Steering without hydraulic power is a rack-and-pinion mechanism where the steering wheel rotates through a cardan system a pinion which moves the rack connected through the rods with steering wheels.

Let us note that in such system, a reduction in force on the steering wheel is achieved either by increasing wheel diameter or by increasing the transmission ratio by means of reducing the diameter of the pinion.

The main disadvantage of this steering control is a strong dependence of the force on the steering wheel and the rotation angle, with corresponding forces and rotation angles of the car wheels. Usually to reduce the steering wheel force, reduce the diameter of the pinion, and, of course, in this case the steering wheel angle increases. It leads to the fact that to reduce the turning radius of the car several turns of the steering wheel needed [17].

The contradiction (CD_1) in this case is: “When the force on the car steering wheel is reduced by increasing the “pinion - rack” ratio, the steering wheel angle is unacceptably increases.”

We begin with Ideal final result (IFR) formulation: “The steering system ITSELF reduces the force on the steering wheel while maintaining the “pinion - rack” ratio.” IFR was achieved (and contradiction resolved) obviously by means of feedback introduction (the principle of "feedback").

2.2 Steering control with servo drive

Let us consider one of the first hydraulic power steering systems – a system where a regulator and an executive mechanism separated (Fig. 4.1 a). Such a system consists of executive mechanism (steering wheel), comparator (slide valve), actuating mechanism (working cylinder), external power source (hydraulic pump) and a feedback system (rods and hinges system) [16].

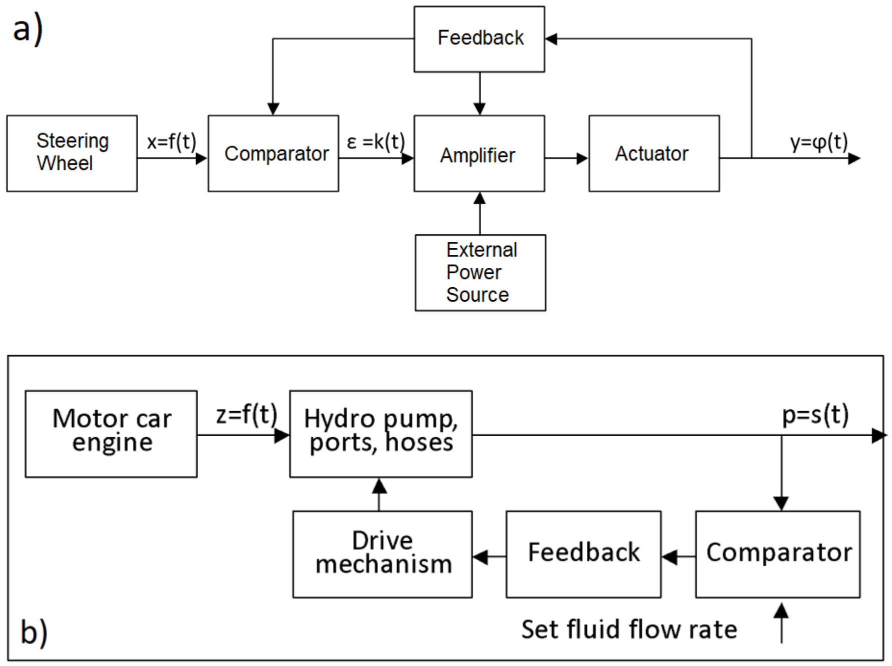

Figure. 4.1. (a) Schematic design of steering with servo drive, x – steering wheel rotation angle; ε – error; y – steering wheels angle. (b) Schematic design of flow rate stabilizing servo with steering wheel constant angle, where z is the engine rpm, p is the outlet flow rate.

This hydraulic power steering works as follows: when turning the steering wheel, the turned upper part of the slide valve directs the working fluid to the required side of the hydraulic cylinder piston, as a result the steering wheels turn. At the same time, the hydraulic cylinder piston rod through the rack mechanism, rotates the lower part of the slide valve to align the rotation angles of the upper and lower parts of it (slide valve), and by this way feedback realizes. In such a system, a small steering effort to move the slide valve is converted in the hydraulic cylinder into a significant effort to turn the car steering wheels (determined by the fluid pressure) [3].

The design has some weaknesses, however [4,5].

1. The working fluid flow rate depends on the engine rpm and therefore the engine rpm also causes the steering wheel feel either light or heavy.

2. The higher the car velocity, the harder the steering wheel rotation and the higher the driver’s fatigue. Let us address these weaknesses one by one.

2.2.1 Hydro Pump Capacity Irrespective of Engine RPM

The power steering pump is driven by the car engine via a drive belt. The pumped fluid flow rate is proportional to the pump speed. As the result, different engine rpm will change the force exerted on the steering wheel which is unacceptable. In typical servo design, the hydro pump schematic diagram is as shown on Fig. 4.1 b).

Let us approach the situation with inventive design tools. We begin with Ideal final result (IFR) formulation: “The pump (or inlet and outlet ports) shall maintain the constant outlet flow rate ITSELF regardless of the engine rpm.” Let us formulate a contradiction (CD_2): “Better flow stabilization makes the hydro pump unacceptably complicated.”

What resources do we have? A material resource is the liquid that returns to the pump, the excess fluid from the pump can be added. Also, the inlet and outlet ports are the resources: the drain valve may be fitted in between (Fig. 4.2) to drain the fluid excess. We can apply the "local quality" and "continuity of useful action" inventive principles: to incorporate a flow control valve in the hydro pump.

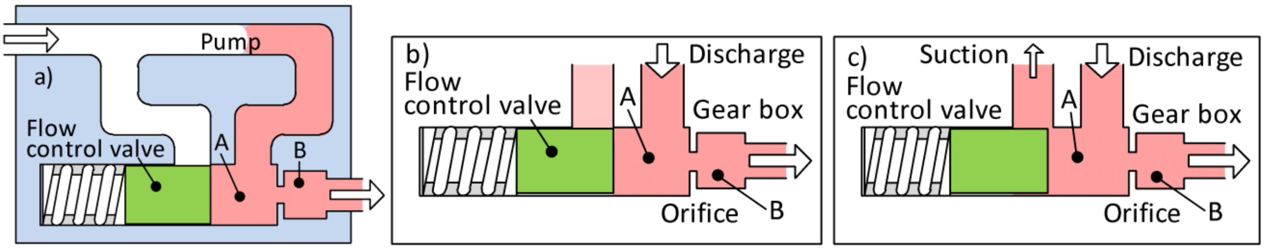

Figure. 4.2. Flow control valve: (a) normal flow; (b) flow slightly increased; (c) flow considerably increased.

With low rpm and constant wheel angle (Fig. 4.2 b), the fluid flows from the discharge line directly to the steering gear through a small opening. As the rpm increases, the fluid flow rate and the pressure in A chamber increases. This allows the flow control valve to overcome the spring force.

The flow control valve starts moving to the left (Fig. 4.2 c) thus enabling the fluid escape through to the suction pipe while excessive pumped fluid is drained (reduced). Thus, the outlet flow rate is stabilized.

On the other hand, the steering wheel turn causes problems. When the driver turns the steering wheel, pressure in B and A chambers in the flow control valve equalizes and the flow control valve shifts to the left. Obviously, more fluid will move from the discharge to the suction channel and the outlet flow rate will decrease. In other words, we face a secondary problem: to stabilize the flow rate against the pressure in the chamber B. For this purpose, the servo schematic diagram should be redesigned (Fig. 4.3 a).

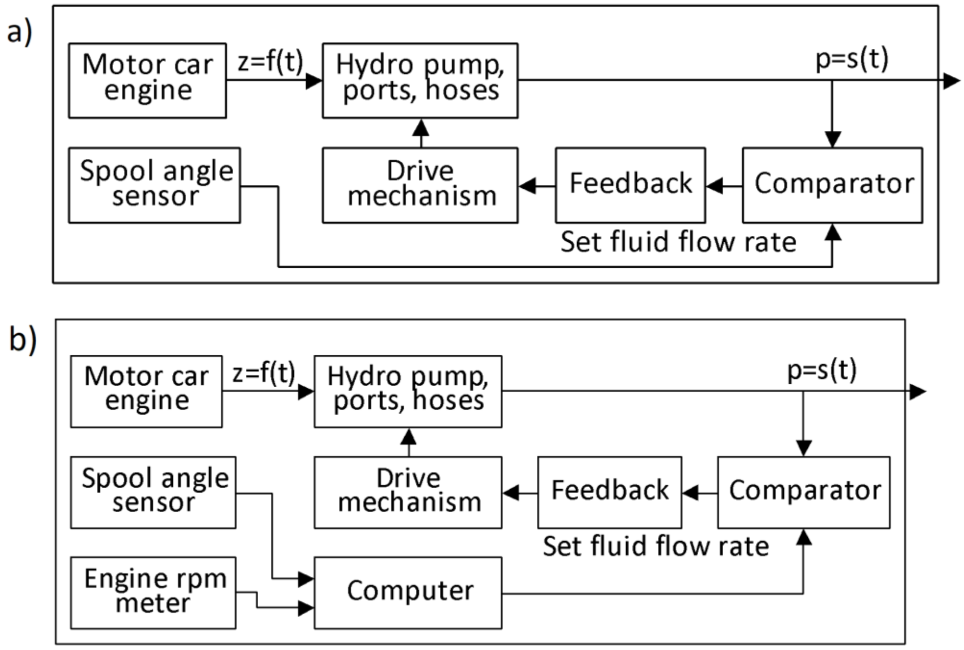

Figure. 4.3 (a) Schematic design of the flow rate stabilizing servo with varying steering wheel angle. (b) The servo schematic diagram of Required Flow Rate and RPM Relationship.

They introduce to the design a control spool position monitoring loop that is directly linked to the steering wheel. The control spool position governs the flow rate.

We approach the situation by the inventive technique again. The formulation of IFR yields: “The flow control valve shall increase the flow rate ITSELF once the control spool position changes”. Let us formulate the contradiction (CD_3): “The improved hydro pump performance (flow rate stabilizing with both stable and unstable steering wheel) makes the hydro pump more complicated.”

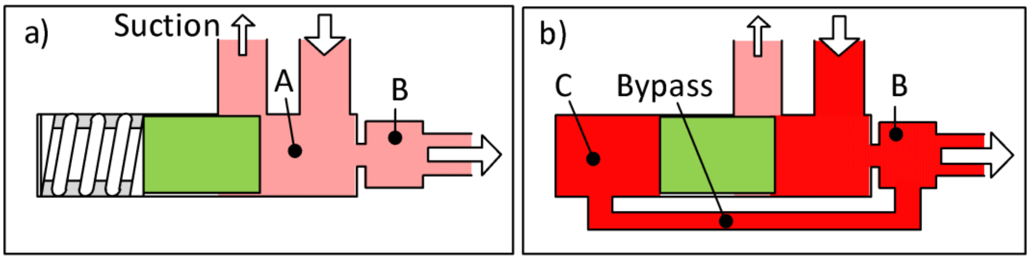

Figure. 4.4. High Flow Rate Stabilizing against Steering Wheel Turn: (a) without pressure feedback, (b) with pressure feedback provided.

What resources do we have? The power source can be in the fluid pressure. Let us ideate around the "feedback" inventive principle. On the left side of the flow control valve, communicate the fluid under the same pressure as in the chamber B. To do this, we introduce the bypass B and C chambers on the left side of the flow control valve (Fig. 4.4). The spring will of course remain in place.

2.2.2 Hydro Pump Capacity Depending on Engine RPM

Let us turn to another weakness of the basic design, i.e. the wheel does not feel heavy at the car high speed [17,18]. To avoid this, the fluid flow to the power steering shall decrease as the car speed increases. At high and very high speed, the engine rpm variation range is minor (speed is mainly depends on the gear ratio). Keeping this in mind, it would be enough to just maintain the required flow rate and rpm relationship with no regard to the gear ratio.

In typical servo design approach, the block diagram (Fig. 4.3 a) should incorporate an engine rpm meter and computer. The resultant schematic diagram is shown on Fig. 4.3 b.

Proceed solving the problem by an alternative technique. Set IFR: “The hydro pump ITSELF shall reduce the flow rate (steering wheel is unstable), against the engine rpm increase.” Let us formulate contradiction (CD$_4$): “Better hydro pump performance (required flow rate and rpm relationship is ensured with both stable and unstable steering wheel) makes the hydro pump unacceptably complicated.”

What resources do we have? Space: A, B and C cavity. Power: Fluid pressure. Use the "feedback" principle to solve the problem: fit the control spool in A cavity that reduces the orifice area against the cavity pressure rise (Fig. 4.4.).

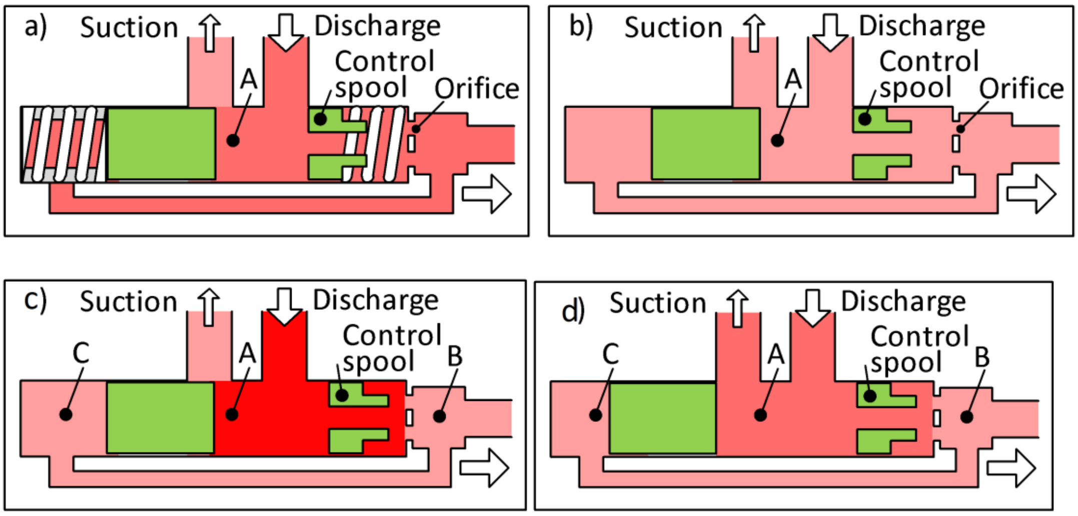

Figure. 4.5 Decrease in fluid flow with increasing rpm: (a) design; (b) low rpm. Flow Rate Decrease against RPM Rise: (c) high rpm, (d) decreasing flow rate.

The control spool is fitted between the flow control valve and orifice. The control spool reduces the flow rate by reducing the orifice area. With low rpm, hydraulic pressure in A cavity is not enough to overcome the spring force and the control spool remains in its position. Therefore there is no flow rate decrease. As rpm increases, hydraulic pressure in A chamber rises and overcomes the spring force and the control spool shifts to the right and partly covers over the orifice. B and C chamber pressure drops. This results in big differential pressure in A and C chambers and the flow control valve shifts to the left and hence the outlet flow rate decreases. The higher rpm the more orifice area is covered by the control spool. This makes the flow control valve shift to the left and the outlet flow rate stabilizes.

As the result, two springs, flow control valve and control spool were able to substitute complex servo design [19] schematic shown on Fig. 4.3 b).

3. Case Study 2: Sway stabilization system conceptual design

Let us illustrate the application of the ideality concept for more model-based control design. We consider the problem of sway stabilization that is very general. It could be found in many engineering fields, for example in crane load stabilization, gondola sway stabilization, free vibration damping in mechanisms etc. Let us assume we observe substantial sway of crane load and need to generate conceptual ideas on its reduction. We would like to provide standard active damping strategy architecture first and to add more concepts, that engage the resources of the object itself. We would like to stress that any TRIZ modelling tool (function model, contradictions, subfields, …) would not develop us any further general strategy “the gondola is to stabilize itself”. The concepts are systematically coming out of the mathematical model of the problem. The model “contains” those physical phenomenon that can be used for self-stabilizing.

We depart from one of the basic models for oscillating body description

$$a_2\ddot{x} + a_1\dot{x} + a_0 x = 0\,, \qquad (1)$$

where $x(t)$ is the oscillation variable, for example pendulum’s angle, and a_i are the oscillator’s parameters. For simplicity reasons we may see a_2 as inertia parameter, a_1 as damping parameter and a_0 as elasticity parameter. We assume small damping in the system ($a_1<<1$), otherwise we would have not been faced oscillation problem at all. Given the initial conditions are non-zero or external impulse force appears (a sharp wind gust), the oscillations of natural frequency f_0 would asymptotically approach its equilibrium point. But it takes too long time.

3.1 Standard feedback control framework

We would speculate that standard feedback stabilization approach means applying an external force *F*. The function *F*(*x*,*t*) is to be chosen in such a manner that the oscillations in the system

$$a_2\ddot{x} + a_1\dot{x} + a_0 x = F(x,t)$$

vanish faster. If such a controller *F*(*x*,*t*) is found the closed loop system is stable itself, the stabilization is automatic.

We can then generate various implementation models within this standard paradigm. For example, the proportional feedback controller *F=kx* for the simplicity. Or PD (proportional-derivative) controller for faster stabilization. Or PID (PI+integrative) controller for better accuracy and elimination of static error etc. The physical embodiment of this formal model(s) with external stabilizing force is not easy but possible. For example, in [7] the force is generated by moving of mass inside the cabin. In the patent [8] the force is generated by the air jet. If the longitudinal motion of the suspension point is controllable, the change of its position is equal to applying an external torque to the load. In this case the load displacement angle can be feed backed to the position of the suspension load, see, for example the patent [18]. Any of controller types discussed above can be applied. But all these standard feedback control concepts would require sensor(s), controller and drive servomotor but do not require any change in the object.

3.2 Inventive design, based on mathematical model

Now, let is return to the model of the object (1). Let us assume now that we can change object design that can be followed by the changes in the governing equations. We are interested in the implementable changes of object design that reduce the settling time or make the object less sensitive to external disturbances. In other words, we are looking for ideal feedback concepts, in which the object stabilizes itself, no feedback is needed. What could be those phenomenon that stabilize the sways?

3.2.1 Anti-resonance absorber

One of the conceptual frameworks could be the passive feedback, in which an absorbing oscillator is added to the design. In the case of pendulum like object the new design would mean two oscillators as in the Fig. 4.6 a). In this case (1) is replaced by

$$\begin{aligned} &a_{12}\ddot{x}_1 + a_{11}\dot{x}_1 + a_{10}x_1 - a(x_2 - x_1) = 0 \\ &a_{22}\ddot{x}_2 + a_{21}\dot{x}_2 + a_{20}x_2 - a(x_1 - x_2) = 0, \end{aligned}$$

where x_i are the oscillator displacements and a_{ij} can be seen as the parameters of the oscillators reflecting inertia, damping factor and gravity constant, a reflects the spring elasticity. Having carefully chosen a_{2i} and a we can show that the magnitude of oscillations at frequency f_0 can be reduced to zero. Thus, the passive damper can effectively attenuate the periodic disturbing force with the most dangerous for (1) dominating frequency f_0.

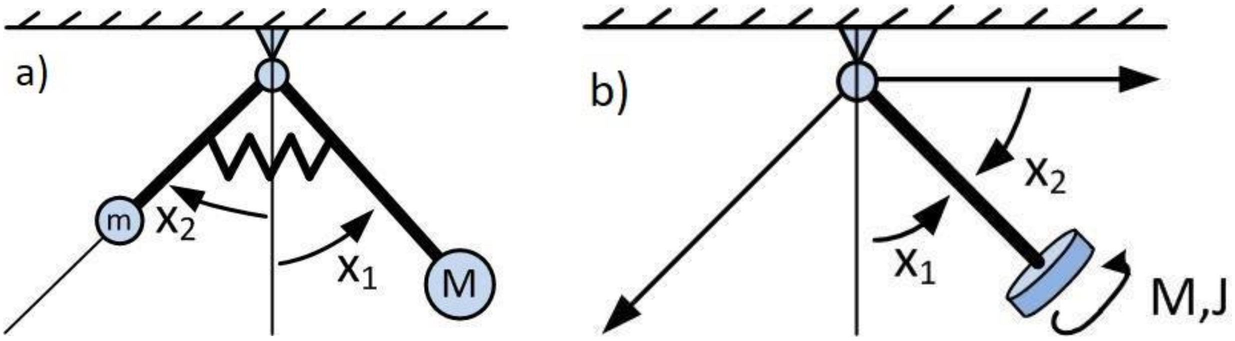

Figure. 4.6. (a) Pendulum stabilization: passive feedback case. (b) Pendulum stabilization: gyroscopic effect in use (here M stays for the external torque).

3.2.2 Self-stabilization by gyroscopic effect

Another idea for self stabilization of (1) is the introduction of gyroscopic effect. More precisely, the gyroscopic effect provides less sensitivity of an object to the external disturbances. The rotation of the load (or a part of the load) can provide the gyroscopic effect for the pendulum. We have to consider a new mathematical model instead of (1)

$$\begin{aligned} a_{12}\ddot{x}_1 + a_{11}\dot{x}_1 - a_G\dot{x}_2 + a_{10}x_1 = 0 \\ a_{22}\ddot{x}_2 - a_G\dot{x}_1 + a_{21}\dot{x}_2 + a_{20}x_2 = 0, \end{aligned}$$

where x_i are the orthogonal deviation angles of the load, a_{ij} represent the parameters of oscillations in these angles and a_G is the parameter of gyroscopic effect (function of the load rotational inertia and rotational rate). The idea made its way to the patents, for example [10].

3.2.3 Variable length pendulum stabilization

Even less obvious phenomena is that the variation of the length of the load suspension can also be used to control its oscillation. Indeed, the mathematical model of the pendulum of variable length can be simplified to the form

$$a_2\ddot{x} + a_1\dot{x} + a(t)x = 0,$$

where $a(t)$ explicitly denotes the variation of the length with time. The model belongs to the class of linear time variant systems. The periodic changes of certain profile (frequency and phase) of the parameter can lead to new form of instability that is called parametric resonance. It is natural to expect that the same periodic changes of different profile (phase) can lead to sway stabilization. The idea is filed as the patent [11].

In all these cases we stayed within the simplest linear mathematical models of the object and its modification. And still were able to mobilize system resources by various linear phenomena (anti-resonance, gyroscopic stabilization, parametric resonance). We can use more careful mathematical modelling that require nonlinear dynamics or we can enlarge the class of possible object modification by those, described by nonlinear differential equations. In the case, the analysis of the oscillation becomes much more complicated but the pallet of physical phenomena becomes much wider. For example, the problem of synchronizing of two oscillators can be analyzed within simpler linear model framework. But the synchronizing would require either direct mechanical linking of the feedback control (“non-ideal design”). Having modeled the situation by nonlinear equations, we can reveal the phenomenon of self-synchronizing (“ideal design”). In fact, any nonlinear differential equation can hide many known and unknown phenomena. They can be mined by the mathematical analysis. In this sense, any “database of physical effects” can never be complete.

4. Case Study 3: Technology process control design

In the previous examples relating to individual devices, it has been shown that the same goals can be easier achievable by changing the design of a technical object, than by creating external feedback control systems. In this section we want to consider similar problems for technological complexes, consisting of a number of units that perform certain technological operations. At the same time, we will try to generalize the concept presented in the previous sections.

The generalization is that the final aim (IFR in terms of TRIZ) is to overcome some certain technical or technological problem with lowest economic costs in the framework of integrated solutions in the field of technology and control. What is more, the most rational projects may be complex and costly in technology, but simple in the implementation of control systems. An opposite situation may arise, when the use of modern tools and control algorithms make it possible to simplify and reduce the cost of technological solutions to the exclusion of the project the number of technological operations and units. Finally, as mostly happens, the most economical and so the most rational solution is not on the edges, but somewhere in the middle, that is, it combines the most sensible technology and control solutions. Due to the complexity of the tasks arising from the presence of this "Golden mean", there are great prospects for the integrated application of scientific and inventive approaches.

As a typical example to illustrate the given thesis let us consider the technological complex of the production of raw mix in cement production [20]. The instability of the chemical composition of the raw mix is due to the chemical heterogeneity produced in the quarries of mixed materials. Let us discuss different ways to ensure the required stability parameters of the raw material mix in terms of the random variations of its components composition.

4.1 Maintaining a constant raw mix formulation

To simplify the real technological process, consider a two-component raw mix of limestone and clay, characterized by the only chemical composition indicator – the percentage of calcium oxide CaO. Let $\beta_1(t)$ and $\beta_2(t)$indicators of chemical composition of two mixed materials in the current time t, $u_1(t)$ and $u_2(t)$are their mass fractions in the mixture. Then from relations of material balance follows a model of mixing operation

$$\beta(t) = \beta_1(t)u_1(t) + \beta_2(t)u_2(t), \quad (4.1)$$

Which determines the dependence of the mixture composition $\beta(t)$ on the composition and proportions of its components.

Geological exploration of deposits of mineral raw materials allows to determine the average mining area characteristics of a chemical composition $\overline{\beta_1}$ and $\overline{\beta_2}$. These data provide the ability to calculate the mass fraction of the mixed materials $\overline{u_1}$ and $\overline{u_2}$which ensure the equality of the average chemical composition of the prepared mixture and specified technological regulations to the value $\bar{\beta}$. The maintenance of constant proportions of mixed materials can be performed with simple control systems with which modern batchers are equipped. A block diagram of the process for preparing the mixture with the maintenance of a constant formulation of the raw mix is shown in Fig. 4.7 a).

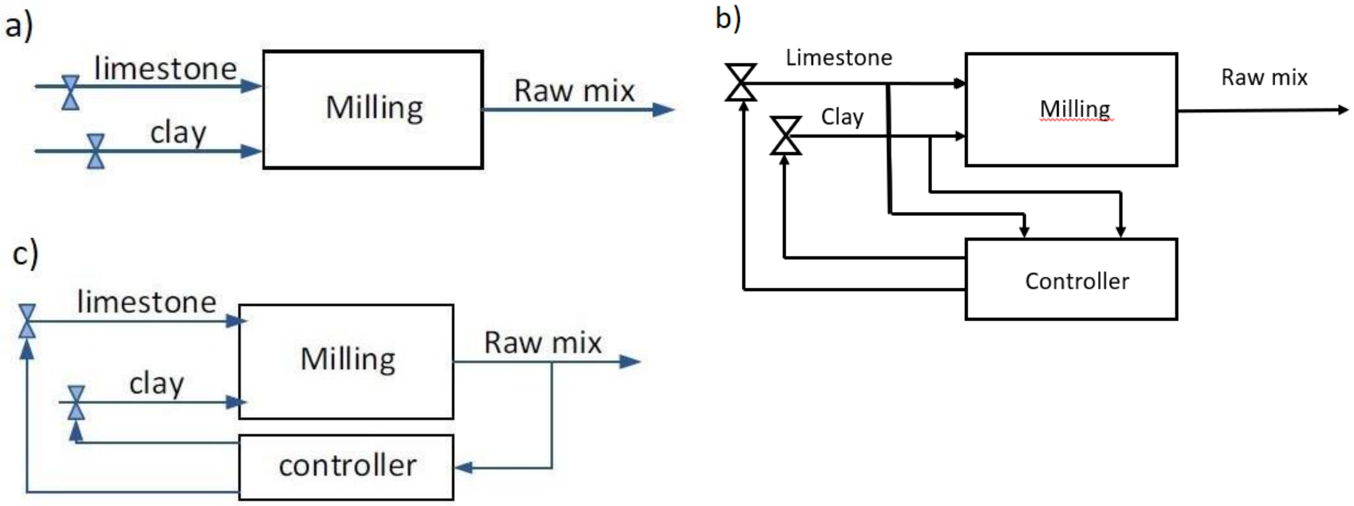

Figure 4.7. Mixing process for cement manufacturing. (a) Without control. (b) Disturbance control. (c) Feedback control design.

As chemical heterogeneity of mineral raw materials exists, as well as due to errors of dosing the indicators of the raw mix composition is different from the calculated values by the value $\Delta\beta(t)$ representing the total perturbations.

Since the perturbations are of a random nature, the theory of random processes should be used to analyze the mixture-preparation scheme. In particular, the magnitude of the perturbations should be assessed according to standard deviation (SD) $\sigma_{\Delta\beta}$. Without going into the mathematics, we present the results of calculations for specific values of parameters, typical for cement manufacture. For the average chemical composition will take the values: $\overline{\beta_1}$= 50%, $\overline{\beta_2}$= 5%, $\bar{\beta}$= 42%, and SD of indicators of the composition of mixed materials $\sigma_{\Delta\beta_1}$ = 2.5%, $\sigma_{\Delta\beta_2}$= 2%. Then, as a result of the calculations, we get: $\overline{u_1}$= 0.82, $\overline{u_2}$= 0.18, $\sigma_{\Delta\beta}$= 2.1%. Compared with the maximum acceptable value σ_{max}= 0.5% indicates that the SD of variations of mixture composition significantly exceeds the technological standard, and therefore the scheme shown in Fig. 4.7 a) does not provide the required stability of the raw mix chemical composition.

4.2 Perturbations control

It is clear that controlling of $\beta_1(t)$and $\beta_2(t)$ make it possible to maintain the composition of the mixture at the required level $\bar{\beta}$, if synchronously with the changes in the composition of the mixed materials, their proportions are appropriately changed. Thus, it would seem that the task of stabilizing the mixture composition at a required level can be simply solved by equipping the technological process control sensors of mixed material current composition, and also a control system which, using obtained information synchronously changes the intensity of material flows. The block diagram of the system control shown in Fig. 4.7 b).

It appears, however, that in real conditions the proposed solution if feasible, then, at least not optimally. The main reason is the difficulty of sufficiently accurate control of the chemical composition of unmilled materials, and also in errors of dosing. Overcoming the difficulties of preliminary control of the mixed materials would require the development of special costly installations for the sampling, preparation and continuous analysis of the chemical composition. In addition, to eliminate dosing errors, it would have to use expensive batchers of raw materials.

4.3 Control with feedback according to the mixture composition data

The above disadvantages of the control by perturbations monitoring can be eliminated if the idea of feedback control used according to the current monitoring of the mixture composition at the outlet of a milling unit. The block diagram of such control system is shown in Fig. 4.7 c).

The advantages of feedback control are that not crushed, but finely milled material is under chemical composition control. With the help of X-ray analyzers, both high accuracy and high speed of determination of the chemical composition of the milled mixture can be achieved. In addition, a single point of control allows to determine reaction mixture composition for both types of perturbations, i.e. to variations in the chemical composition of raw materials and to the errors of their dosage. From an economic standpoint, it is important also that unlike the previous control scheme, where each raw component should be analyzed for its appliance, when using feedback only one analyzer of chemical composition is needed.

In order to understand the satisfaction of such a system for assigned task – stabilization of the mixture composition – it is needed to evaluate the SD of the output variable, i.e. the milled mixture chemical compositionм $\beta_m(t)$. If simply take to a milling unit the model of transport delay, and for the correlation function of given perturbation $\Delta\beta(t)$ use a frequently used approximation $R(\theta) = \sigma_{\Delta\beta}^2 \exp(-a|\theta|)$ (where a characterizes the smoothness of the perturbation of the milling output) it is possible to obtain the required estimate achievable level of stability in the control system with feedback [13]. We assume that the total delay in the system resulting from the transport delay in technological process and the delay of chemical analyzes is 1 h. Adding to the previous example, the numerical values for the newly introduced parameter $a = 0.3h^{-1}$, get the estimated value SD of the mixture at the milling output $\sigma_{\Delta\beta_m}$= 1.4 %, which significantly exceeds the allowed maximum $\sigma_{max} = 0.5\%$. Thus, despite the advantages of the system for controlling the proportions of the materials being mixed, which actively uses the current information about the output characteristics of the process, it does not solve the task – to achieve the required degree of stability of the chemical composition of the raw mix. The main reason of this fact lies in a significant total delay in the control loop, which does not allow to control system to suppress high-frequency components of perturbations.

4.4 Homogenization systems application

Moving on to the IFR, let us turn to the analysis of the perturbations effective smoothing possibilities by purely technological methods. To do this, we supplement the process with the homogenization of the milled raw mix (Fig. 4.8 a) [20].

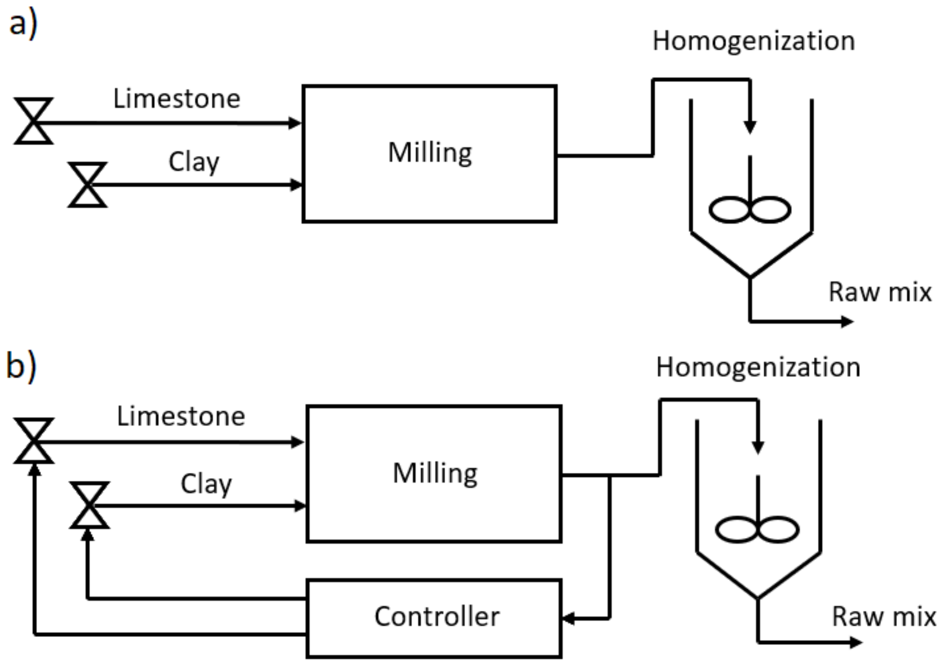

Figure. 4.8. Scheme of process with mixture homogenization. (a) Without control. (b) Control system in combination with homogenization system.

Homogenizers used in industry represent a container with forced intensive mixing of entering material [20]. The energy cost of homogenization nonlinearly grows with increasing capacity, so for economic reason it is needed to minimize the volume of the homogenizer. In order to calculate the required volume of homogenizer, the mathematical model is necessary. The simplest mathematical description of homogenization in averaged capacity gives the model of an ideal mixer [21]. It shows how the chemical composition at the output of the flow homogenizer $\beta_a(t)$ varies depending on changes in the chemical composition of the material flow at its input $\beta_m(t)$. The only model parameter T equal to the time of filling of the averaged capacity.

Using the ratios of the statistical dynamics, we can calculate the SD of the output variable $\beta_a(t)$ for various values of T with respect to the scheme shown in Fig. 4.8 a) with the homogenizer, which supports constant proportions of mixed materials. As a result, it can be found the smallest needed homogenizer filling time T_{min} to guarantee the required blending ability. For the considered parameter values $T_{min} = 56h$. With a representative for cement production lines productivity $Q = 100t/h$, the minimum capacity of the averaged capacity should be 5600t. Such a significant amount, entailing both large capital costs for the construction of a homogenizer, and the serious operating costs of forced homogenization, motivates to the search for better methods of solving the original problem.

4.5 The combined use of feedback control and systems of homogenization

It is known that the averaging systems are well suppress high-frequency perturbations, but do not cope well with low frequency. The feedback control systems, on the contrary, effectively compensate low frequency components of the disturbances, but because of the significant delay can't handle high-frequency perturbations. Taking into account these both circumstances, it is hoped that the significant technological benefits can be achieved by combined use of mixed materials proportions control discussed in section 4.3 and averaging the milled mixture in containers equipped with a homogenization system discussed in section 4.4. The block diagram of such a system is shown in Fig. 4.8 b).

Calculations show that the minimum value of the homogenizer filling time is $T_{min} = 3.55h$ [13]. With productivity equals to $Q = 100t/h$ the minimum capacity of the averaging capacity is 355t, which is 15 times less than in a scheme that does not use feedback control. Without giving here specific cost values about implementation of both compared schemes of mixture production it can be safely asserted that the scheme obtained by the serial connection of mixing controlled part with working in pass-through mode, low capacity homogenizer is much better in economic terms than the uncontrolled scheme with a large homogenizer. At the same time, it appears that the economic effect can be increased further if consider that the aim of the control scheme with the homogenizer should be achievement of the minimum SD of the mixture composition not at the milling output, but at the homogenization output. The point is that the feedback control algorithm has to compensate the perturbations predicted for the time delay in the control loop. In the scheme with forced averaging, compensation of perturbations is needed at the output of the homogenizer. As perturbations at the output of the homogenizer contain only relatively low frequency components, their prediction for the delay time is much more efficient than at the milling output. Hence the additional effect of reducing the SD of the output variable $\beta_a(t)$. It can be quantitatively estimated using statistical dynamics of control systems [13]. The minimum time of homogenizer filling $T_{min} = 1.25h$, when productivity $Q = 100t/h$; the minimum capacity of averaging tank is 125t, which is almost 3 times less than in the scheme where controlled mixture production part and homogenizing part considered separately.

So, by combining heuristic considerations of inventive nature with the exact calculations performed with the use of statistical dynamics of control systems [22], it makes it possible to significantly move to what called IFR in TRIZ. However, the end point in this movement has not been achieved (and, most likely, will never be achieved), since there is still a problem of reducing the energy costs for forced homogenization. The solution can be sought in the direction of a fundamental redesign of the homogenizer. The system of forced homogenization should be replaced by the sequence of technological operations of separation of the input flow for a number of "subflows", with waiting for each "subflow" in the buffer tank for some time and then the subsequent merging of the "subflows". Right choice of the intensities of the "subflows", which should be calculated with statistical dynamics, should lead this system to desired averaging effect without any significant energy costs.

Since this inventive idea is still in the research stage, we will not go into details. Let's just say that here we need a simple control system that will have to maintain the required values of the intensities of "subflows" at the calculated values.

We demonstrated on the specific example, that optimal solution may not be to abandon the control process in favor of purely technological methods. Also, as shown, the purely controlling methods as another extreme not always leads to the achievement of the IFR. The optimal solution was found in combination of the technological object and controlling it automation as a combination of two modified parts of a single complex [12]. In this case, it is possible to take into account and use the beneficial properties of both components in the most reasonable manner.

Simplified nature of considered example made it possible to perform analysis in an analytical way. In a real situation, when:

- The mixture does not consist of two, but of a larger number of components;
- The chemical composition is characterized by not one, but several parameters;
- Along with mixture homogenization, prior mixed materials averaging can be used;
- The more or less accurate batchers can be chosen;
- There are alternatives in control methods of chemical composition;
- For milling, homogenizing, and prior averaging units of different type and size can be used.

Behavior analysis of system “Object-Controller” under random perturbations is seriously complicated [23]. Mostly such studies carried in the computer simulation and automated comparative analysis of various options according to their technological efficiency and value characteristics [24]. However, the general sense of the problem, optimization of economic indicators with technological requirements is still saved.

Moreover, man-machine decision nature is compounded, because the preliminary selection role which requires the experience of design-technologists and design-managers is increased by the reason of the huge number of options and complexity of formalizing. Eventually, fruitful results can be expected only in the connection of experience, based on it inventions and scientific approaches which allow to get the quantitative evaluation of the effectiveness and suitability of various alternatives [14].

Conclusions

The study provides an idea for alternative (inventive) approach to design automation. It is shown how the concepts of Ideal final result and, contradiction analysis of TRIZ assist simplifying the controller design by inventive changes in the plant. The use of mathematical model of the plant can enrich the design ideas due to additional domain of resource analysis.

Three examples demonstrate the approach to inventive automation design. In the two examples the object design is changed in such a way that the control feedback is either not required or it becomes much simpler. The third example related to technological complexes, demonstrates the generalizing idea. Its meaning is that the optimal economic plan combines the capabilities of technology and management should be formed on the basis of experience, invention and science.

The future research will focus on the systematization of heuristic methods in controller design and the development the concurrent plant and control design in the framework of control theory.

Acknowledgements

L.Chechurin would like to acknowledge the support of TEKES, Finnish agency for innovation support and its Finnish distinguished professor (FiDiPro) program.

The authors would like to acknowledge the EU Marie Curie program INDEED project for its support.

References

[1] Marcus, R. Hydraulic Power Steering System Design in Road Vehicles Analysis, Testing and Enhanced Functionality Linkoping 2007 ISBN 978-91-85643-00-4.

[2] Karim, N. How Car Steering Works, last visited 14 July 2016 http://auto.howstuffworks.com/steering4.htm.

[3] Flow control device of power steering apparatus, Susumu Honaga and others, Patent US 6041807 A (1997).

[4] Fluid pressure control device in power steering apparatus, Takeshi Futaba, Masahiko Noguchi, Patent US 4619339 A (1984).

[5] Power steering apparatus, Kyosuke Haga and others, Patent EP 0562426 A1 (1992).

[6] Control apparatus for power-assisted steering system, Toyoda Koki Kabushiki Kaisha, Patent EP 0430285 A1 (1989).

[7] Active control system to stabilize suspended moving vehicles in cables. Vieira, Danilo Martins, Ibrahim, Ricardo Cury, Torikai, Delson. ABCM Symposium Series in Mechatronics – 2010, vol. 4 - pp.120-126.

[8] Mechanism for swing damping and leveling of the load. Kokoev M.N. Patent RU 2141926, (1999)

[9] Method for damping the load swing of a crane. Olli Mård, Risto Ahvo, Patent US 5799805 (1994)

[10] Mechanism for load swing damping hanged by crane, Behbudov M,B., Goldobina L.A., Patent RU 2224708, (2001)

[11] A method of stabilizing of output signal of oscillating system. Chechurin S., Chechurin L., Mandrik A., Patent RU 2393520, (2009)

[12] Sharifzadeh, M. Integration of process design and control: A review. Chemical Engineering Research and Design, 2013. vol. 91(12), pp.2515-2549

[13] Yakovis L., Chechurin L. Systematic Design of Automated Processing Complexes » 25th International Conference on Flexible Automation and Intelligent Manufacturing - FAIM, International conference on flexible automation and intelligent manufacturing, 2015,vol. 1, pp. 438-445

[14] Yakovis, L., Chechurin, L. Creativity and heuristics in process control engineering, Chemical Engineering Research and Design, 2015, vol. 103, pp. 40-49

[15] Active control system to stabilize suspended moving vehicles in cables. Vieira, Danilo Martins, Ibrahim, Ricardo Cury, Torikai, Delson. ABCM Symposium Series in Mechatronics – 2010, vol. 4 - pp.120-126.

[16] Kloos T., Pfeffer P.E. (2017) Steering system models – an efficient approach for parameter identification and steering system optimization. In: Pfeffer P. (eds) 8th International Munich Chassis Symposium 2017. Proceedings. Springer Vieweg, Wiesbaden DOI 10.1007/978-3-658-18459-9_36, Print ISBN978-3-658-18458-2, Online ISBN978-3-658-18459-9

[17] Power steering apparatus, Kyosuke Haga and others, Patent EP 0562426 A1 (1992).

[18] Brunner S., Harrer M. (2017) Steering Requirements: Overview. In: Harrer M., Pfeffer P. (eds) Steering Handbook. Springer, Cham. DOI 10.1007/978-3-319-05449-0_3, Print ISBN978-3-319-05448-3, Online ISBN978-3-319-05449-0

[19] Brunner S., Harrer M., Höll M., Lunkeit D. (2017) Layout of Steering Systems. In: Harrer M., Pfeffer P. (eds) Steering Handbook. Springer, Cham. DOI 10.1007/978-3-319-05449-0_3, Print ISBN978-3-319-05448-3, Online ISBN978-3-319-05449-0

[20] W. H. Duda, Cement-Data-Book, Volume 2, Electrical Engineering. Automation. Storage. Transportation. Dispatch, Bauferlag GmbH, Wiesbaden and Berlin, 1984.

[21] T. J. Fitzgerald, “Theory of blending in single inlet flow systems,” Chem. Eng. Sci., vol. 29, no. 4, pp. 1019–1024, 1974

[22] K.J. Astrȍm, “Introduction to stochastic control theory”, Academic Press, N.Y., 1970.

[23] I. Gorenko, S. Doroganitch, and L. Yakovis, “Multilevel process control in multi-component mixtures blending,” presented at the The 10th World Congress on automatic Control, Munich, 1987, vol. 2, pp. 218–222.

[24] S. Doroganitch, J. Edvabnik, E. Shtengel, and L. Yakovis, “Optimization of parameters of automated process complex for raw mix preparation,” presented at the The Second NCB International Seminar on Cement and Building Materials, New Delhi, 1989, pp. 56–63.