

THE ALIGNMENT OF PERFORMANCE MEASUREMENT WITH THE MANUFACTURING SYSTEM DESIGN

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ABSTRACT

A company's performance measurement system drives its behavior and thus, affects its ability to achieve its strategic objectives. Therefore, developing performance measures that are aligned with the enterprise objectives plays a crucial role in accomplishing a company's long-term goals. This paper explains the cause and effect relationships between performance measurement and manufacturing system design from a system design perspective. As an example, it is illustrated why current performance measurement methods cause plants to evolve into mass production systems. Based on this understanding, this paper discusses the usefulness of the axiomatic design approach to develop performance measures that are aligned to the objectives of a company. Furthermore, a new strategic performance measurement method is proposed by using the manufacturing system design decomposition, which is a generic design model for manufacturing system design based on the axiomatic design method.

Keywords: Performance Measurement, Axiomatic Design, and Manufacturing System Design.

1 INTRODUCTION

The behaviors of systems as well as the ability to achieve strategic objectives are affected by the way systems are measured. It is often true that the strategic goals of an organization are not achieved due to the complex interactions within the organizational hierarchy. In the lower levels of the organization, the performance measures, not the strategic objectives drive the behavior of the employees since they seek to make their performance measures look good. For this reason, an improper set of measurements can lead to dysfunctional or unanticipated behavior, which does not contribute to the organization objectives [Fry (1995)].

According to Wisner and Fawcett [Wisner and Fawcett (1991)], the role of performance criteria is twofold. First, it provides a firm with a method to assess its current competitive position with respect to its competitors and the demands of the market, and to identify avenues for improvement. Second, it monitors the firm's progress in moving towards its strategic

objectives. From this point of view, it is repeatedly argued that the greatest problem associated with traditional performance criteria is the failure to provide sufficient guidance in the formation of tactical decisions to achieve simultaneous objectives [Eccles (1991)], [Wheelwright (1978)]. An enterprise production system must be designed to achieve the goals of cost, quality, flexibility and delivery time simultaneously [Suh, Cochran, and Lima (1998)]. The simultaneous achievement of these goals at the lowest possible cost is the manufacturing system design problem.

The manufacturing system design decomposition has been developed to illustrate the simultaneous goal and solutions that must be considered when implementing a manufacturing system [Suh, Cochran, Lima (1998)]. Performance measures should be tied to the enterprise or production system design and thus help sub-systems to achieve the functional requirements of the organization, which will eventually contribute to the goals of a company. To achieve long-term goals of a company, it is very important to develop and maintain the right performance measures at each organizational level those are aligned with the enterprise objectives [Cochran (1994)].

In this paper, the cause and effect relationships between performance measurement and manufacturing system design are explained from a system design perspective. As an example, it is first illustrated why current performance measurement methods cause plants to evolve into mass systems. Figure 1 illustrates that the performance measures significantly affect the manufacturing system design. To achieve the system design objectives, it is proposed that the performance measures must be aligned with the Functional Requirements (FRs) of the Manufacturing System Design (MSD). The design of the manufacturing system must be based on the manufacturing strategy, which is affected by many elements (see Figure 1).

Given the preceding explanation, a strategic performance measurement methodology is proposed by using the Manufacturing System Design Decomposition (MSDD), which provides a communication and design tool to define the objectives, called Functional Requirements (FRs) and corresponding design solutions, called Design Parameters (DPs) for an organization based on the axiomatic design methodology [Carrus and Cochran (1998)]. Figure 1 illustrates that the Performance Measures (PMs) must be derived from the FRs of the MSDD. The usefulness of the axiomatic design approach to

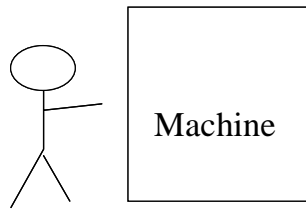


Figure 4. Traditional One Machine per One Operator Situation

Enterprises that utilize equation (1) as their cost accounting system attempt to reduce unit cost by determining at least three FRs which affect the mass manufacturing system design.

- FR 1: Eliminate the need for direct labor: $DL_p \rightarrow 0$
- FR 2: Increase the number of units / time to infinity: $N_p \rightarrow \infty$
- FR 3: Reduce labor wage: $W_{dl} \rightarrow 0$

It is assumed that C_m cannot be decreased in the preceding analysis.

To eliminate the need for direct labor, automated machines are implemented as the design parameter (DP) to minimize the direct labor time (see Figure 5). The second FR to achieve unit cost reduction is to maximize the number of units produced during a certain time interval. Increasing the processing speed of the machine becomes the DP to achieve this FR (see Figure 6). The third FR to minimize the unit cost is to directly reduce the labor wage. Moving plants to low-wage countries is now a popular DP to achieve this FR (see Figure 7).

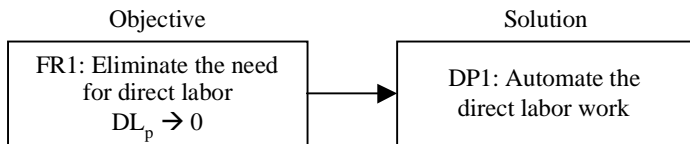


Figure 5. FR 1 and DP 1

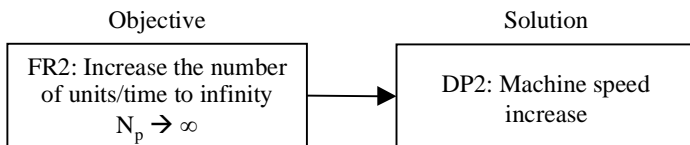


Figure 6. FR 2 and DP 2

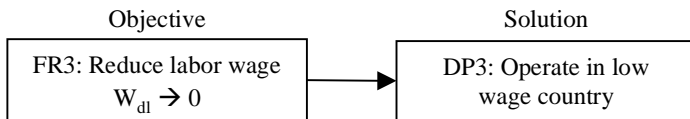


Figure 7. FR 3 and DP 3

2.2 MASS MANUFACTURING SYSTEM DESIGN AS A RESULT OF THE UNIT COST EQUATION

The effect of the unit cost equation is profound with respect to manufacturing system design. It has led management to envision the concept of the “lights out factory” [Hampton (1988)].

2.3 THE DECOMPOSITION OF THE MASS MANUFACTURING SYSTEM DESIGN

As shown in Figure 8, one of the primary goals of a company may be to maximize the long-term return on investment (ROI). The return on investment is calculated by Equation (3). To maximize the return on investment, the FRs become: increase sales revenue, minimize production costs, and minimize production investment. However, the way to achieve these FRs can be different depending on the market environment. For example, in the 1910s, when the Ford model T was introduced, the pre-sale rate was over 98% [Arnold and Faurote (1915)]. Ford could sell whatever quantity was produced. Therefore, the DP for the first FR (increase sales revenue) was to maximize production output. Similarly, the DP for the second FR, (minimize production costs) was to produce at minimum unit cost. In addition, to maximize machine utilization became a DP for the third FR (minimize production investment). These FRs and DPs are summarized in Figure 8.

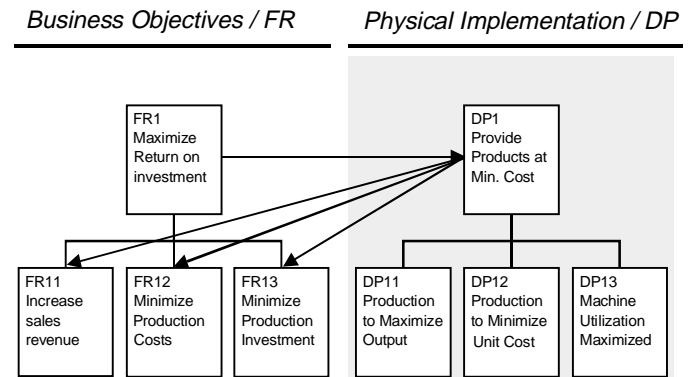


Figure 8. The Decomposition of the Mass Manufacturing System Design

$$ROI = \frac{Sales - Cost}{Investment} \quad (3)$$

The design decomposition shown in Figure 8 is a rational design solution to achieve the FRs considering the market conditions of Henry Ford’s era. The design equation in this case is shown in Equation (4) [Suh, Cochran, and Lima (1998)]. The design matrix shows that this is a decoupled design.

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \end{bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \end{bmatrix} \quad (4)$$

To illustrate the impact of the unit cost equation on the manufacturing system design, further decomposition of the mass system design is shown in Figure 9. In this decomposition, DP12 - Produce at Minimum Unit Cost is decomposed. As shown in Figure 9, five FRs result from the decomposition of DP12.

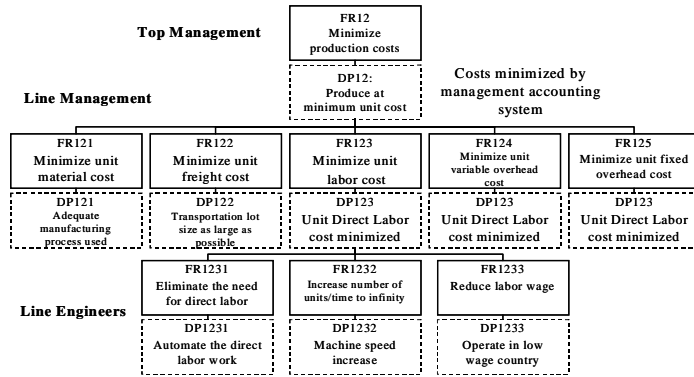


Figure 9. Further Decomposition of Mass Production System – Line Management Level

This design is an incomplete design from the axiomatic design point of view since one DP (DP123) is used to achieve three FRs (FR123, FR124, and FR125) [Suh (1990)]. Equation (5) indicates that the unit cost equation reinforces the use of DP123 to reduce the perceived unit cost.

$$\begin{bmatrix} \text{FR121} \\ \text{FR122} \\ \text{FR123} \\ \text{FR124} \\ \text{FR125} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \\ 0 & 0 & X \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{DP121} \\ \text{DP122} \\ \text{DP123} \end{bmatrix} \quad (5)$$

The design equation clearly shows the emphasis on decreasing of unit direct labor cost. As previously discussed, there are three approaches for reducing the unit cost by reducing unit direct labor cost. These approaches provide the next level of the mass manufacturing system design decomposition. It is essential to notice that automation, manufacturing in low wage countries and the design and operation of high-speed machine are options for unit cost reduction. The next layer of the mass production decomposition is best illustrated by Figure 10.

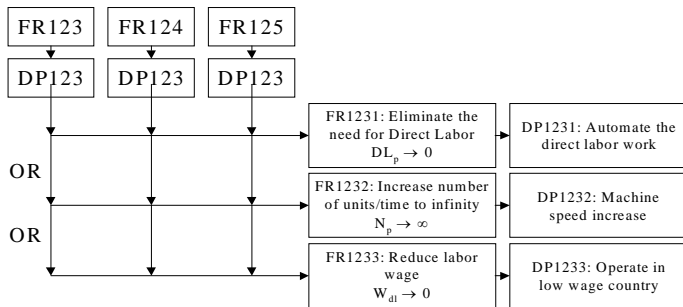


Figure 10. Further Decomposition of Mass Production System – Minimization of Direct Labor Cost

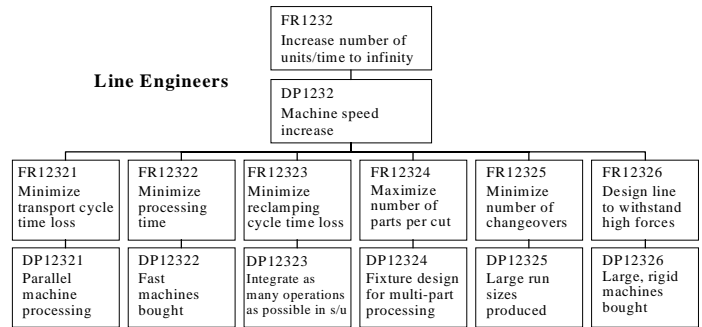


Figure 11. Design Decomposition of Unit Labor Cost Minimization – Line Engineers Level

Further decomposition of the unit direct labor cost reveals design parameters that characterize current mass production plant design and operation. In Figure 11, one of the sub-FRs to minimize the unit direct labor cost (FR1232) is further decomposed using the zig-zagging process.

2.4 SYSTEM DYNAMICS EXPRESSION OF ADVERSE EFFECTS OF UNIT COST EQUATION IN MASS MANUFACTURING

Figure 12 shows how manufacturing processes in the traditional mass manufacturing system have evolved toward meeting the performance measures of the unit cost equation. The current unit cost equation, as a sole dominant factor among the performance measures of production system and equipment design, leads to improvement of operation, instead of the manufacturing system design. The dotted lines in the Figure 12 illustrate the negative side affect of the unit cost equation. The irony is that the negative interactions eventually undermine the highest and original FR of the unit cost equation, which is to produce at minimum unit cost. Due to these intangible side effects, these production system optimization practices based on the unit cost equation may not achieve the ultimate goal, which is the long-term profitability of the enterprise.

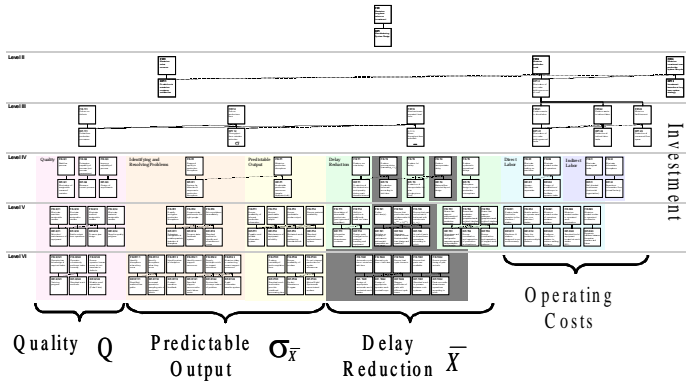


Figure 14. Manufacturing System Design Decomposition Reflecting Today's "Lean" Manufacturing Objectives

With this design decomposition, the differences between equipment design in "lean" and "mass" plants can be explained. By looking at some characteristic FR-DP pairs in this chart, it is recognized that the equipment in mass manufacturing systems is the result of operation-focused thinking while the equipment in lean production systems is the result of a new system design thinking, which uncouples labor cost from the speed of the machine. To reduce labor cost, operator's work content is matched to the customer demand cycle time. To reduce cost, the motions of the operator are decreased (see Figure 15, panel B). A machine represents the physical integration, which is necessary to satisfy multiple FR-DP pairs that are functionally independent by definition from the decomposition (Figure 16). The machine in Figure 15, panel B, achieves multiple FR-DP pairs as defined by the manufacturing system design decomposition. The FRs and DPs, which a machine must meet in this new manufacturing system design, are listed in Table 1.

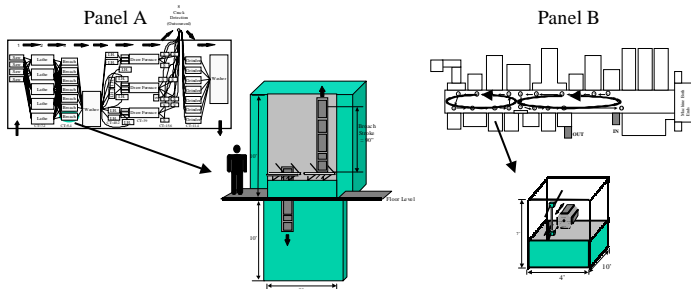


Figure 15. Comparison of Mass and Lean Broach Machine Design [Cochran and Dobbs, 1999]

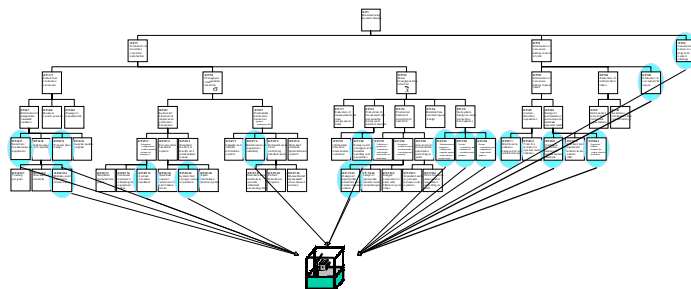


Figure 16. FR-DP Pairs Affecting Machine Design

Table 1. FRs and DPs Affecting Equipment Design

FR	DP
FR-Q11 Eliminate machine assignable causes.	DP-Q11 Selection / maintenance of equipment

FR-Q13 Eliminate method assignable causes.	DP-Q13 Process plan design
FR-Q123 Ensure operator human errors do not translate to defects.	DP-Q123 Mistake proof operations (Poka-yoke)
FR-R113 Identify nature of disruption.	DP-R113 Context sensitive feedback
FR-P12 Ensure predictable equipment output.	DP-P12 Maintenance of equipment reliability
FR-T12 Ability to produce in sufficiently small run sizes	DP-T12 Design quick changeover for material handling and equipment
FR-T221 Automatic cycle time <= minimum takt time	DP-T221 Design of appropriate automatic work content at each station
FR-T51 Ensure that support resources don't interfere with production resources.	DP-T51 Subsystems and equipment configured to separate support and production access requirements
FR-T52 Ensure that production resources (people/automation) don't interfere with one another.	DP-T52 Ensure coordination and separation of production work patterns
FR-T53 Ensure that support resources (people/automation) don't interfere with one another.	DP-T53 Ensure coordination and separation of support work patterns
FR-D11 Reduce tasks that tie the operator to the machine/station	DP-D11 Machines & stations designed to run autonomously
FR-D21 Minimize wasted motion of operators between stations.	DP-D21 Configure machines/stations to reduce walking distance
FR-D23 Minimize wasted motion in operators' work preparation	DP-D23 Ergonomic interface between the worker, machine and fixture
FR123 Minimize facilities cost	DP123 Reduction of consumed floor space
FR13 Minimize investment over production system life cycle.	DP13 Investment based on a long term system strategy

(note: FR-Qs: FRs in quality branch, FR-Rs: FRs in identifying and resolving problems branch, FR-Ps: FRs in predictable output branch, FR-Ts: FRs in delay reduction branch, FR-Ds: FRs in direct labor branch, FR-Is: FRs in indirect labor branch)

3.2 ALIGNING THE PERFORMANCE MEASURES (PMS) WITH THE MANUFACTURING SYSTEM DESIGN

Since the manufacturing system design decomposition reflects general FRs of manufacturing system, the performance measures derived from it are also generally applicable to many types of manufacturing environment. Figure 1 illustrates when performance measures are clearly aligned with the FRs of the manufacturing system design. The performance measures are aligned to the FRs of the decomposition according to three levels of management. Details of the performance measures according to the levels of management are presented in the Appendix.

3.3 CHARACTERISTICS OF COST ACCOUNTING SYSTEM AS A PERFORMANCE MEASURE

According to Hiromoto [Hiromoto (1988)], it is noteworthy that in order to make accounting policies subservient to corporate strategy, Japanese manufacturing strategy places high premiums on quality and timely delivery in addition to low-cost production.

Thus “lean” companies make extensive use of non-financial measures to evaluate factory performance.

Unlike accounting systems that support the preparation of periodic financial reports, cost accounting systems are not subjective to rules or standards such as generally accepted accounting principles. Therefore, there is no reason to think that there is a unique right cost accounting system. Enterprise can develop its own cost accounting system based on the market environment and long-term strategy. What is important is that a cost accounting system should have the characteristics previously presented to be aligned with the enterprise objectives.

Equation (6) is a proposed template of the new unit cost equation from the manufacturing system design decomposition.

Quality cost includes the influence of all quality problems of a product. That is, it should include not only the cost due to scrap and rework which take place within the factory, but also all the losses which are generated after products are shipped to the customers. Throughput time cost terms represents all the losses that take place when a manufacturing system fails to deliver products on time and meet customer expected lead-time. Overhead allocation should be determined in a manner that guarantees that there is no product cost distortion. It is clear that there is no unique correct way to estimate all the cost terms in equation (6). Finding a reasonable way to estimate these terms is a rigorous research topic. For this reason, we have proposed the approach given by Figure 1 to align performance measures to the manufacturing system design.

$$\alpha = \frac{C_Q + C_{NI} + C_T(\bar{X}) + C_T(\sigma_X) + C_{DL} + C_{IDL} + C_M + C_{INV}}{N_p}$$

where α = unit cost

C_Q = quality loss

C_{NI} = opportunity cost due to not improvable system

$C_T(\bar{X})$ = opportunity cost due to mean throughput time (6)

$C_T(\sigma_X)$ = opportunity cost due to on - time delivery

C_{DL} = direct labor cost

C_{IDL} = indirect labor cost

C_M = material cost

C_{INV} = investment

N_p = number of parts produced

4. CONCLUSION

The true objective of the performance measurement system is to help management keep its enterprise competitive by adding value to the products and enhancing customer satisfaction. Again, in today's market, the factors that make products competitive include not only cost but also non-financial factors such as quality and delivery time. Therefore, performance measures should reflect these non-financial aspects so as to guide the system design to be more competitive. For this reason, axiomatic design is very useful to develop the right performance measurement system that will serve the real objectives of a firm. Axiomatic design reveals the cause-effect relationships of the functional requirements of a system and the corresponding design parameters and clearly presents them by the design decomposition procedure. Therefore, the development of a useful performance measurement system that reflects the goals of the system design is greatly facilitated.

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6. APPENDIX

Top management level – high level FRs

The performance measures of top management are derived from the high level FRs of the manufacturing system design decomposition. Financial performance measures that include revenue, cost, and investment are derived from the highest level of FRs while one lower level of FRs should be also considered to ensure these measures are valid for a long term. They are listed in Table 2.

Table 2. New Performance Measures for Top Management

FR	PM
FR11 Maximize sales revenue	Sales revenue
FR12 Minimize production cost	Production cost, Cost reduction
FR13 Minimize investment	Investment as % of sales
FR111 Deliver no defects	Quality (number of defects)
FR112 Deliver products on time	On-time delivery %
FR113 Meet customer expected lead time	Throughput time / minimal throughput time

Middle management level – middle level FRs

At the middle management level or product line management level, the performance measures may vary with the responsibilities of individuals. However, some common performance measures are also needed since middle management is responsible for some portion of the organization. In general more specific performance measures appear since more specific FRs are developed to support higher level FRs. Some of the performance measures are listed in Table 3.

Table 3. Examples of Performance Measures for Middle Management

FR	PM
FR-Q1 Stabilize process	Process capability, First time through production %
FR-Q3 Improve capability of process	Process capability improvement over time
FR-R1 Respond rapidly to production disruptions	Mean time to repair, line downtime to fix problems
FR-P1 Minimize production disruptions	Mean time to failure, unplanned line downtime
FR-T1 Reduce run size delay	Run size
FR-T2 Reduce process delay	% of subsystems operating at customer takt time
FR-T3 Reduce lot delay	Transportation lot size
FR-T4 Reduce transportation delay	Total transportation distance
FR-T5 Reduce systematic operational delays	Amount of production shortfall due to interference
FR121 Reduce waste in direct labor	% of value-adding work time of direct labor
FR122 Reduce waste in indirect labor	% of support time of indirect labor
FR123 Minimize facilities cost	Floor space consumed

Line engineers level – lower level FRs

At this level, more non-financial specific performance measures are derived. However, following the hierarchical structure of the design decomposition, the relationship with high-level performance can be easily identified. As with the performance measures for middle management, only some examples are presented in Table 4 due to the diverse nature of line engineers' work content.

Table 4. Examples of Performance Measures for Line Engineers

FR	PM
FR-Q11 Eliminate machine assignable causes	Number of defects caused by machine errors
FR-Q121 Operator has knowledge of required tasks	Number of defects caused by operator's lack of knowledge
FR-Q122 Operator consistently performs tasks correctly	Number of defects caused by non-standard work methods.
FR-Q123 Ensure operator human errors do not translate to defects	Number of defects caused by human error
FR-Q13 Eliminate method assignable causes	Process capability of the method used
FR-Q14 Eliminate material assignable causes	Number of defective parts received
FR-Q3 Improve capability of process	Process capability improvement over time for each machine
FR-R11 Rapidly recognize production disruptions	Mean time to recognize disruptions (where, when, what)
FR-R12 Communicate problems to the right people	Mean number of people contacted to solve disruptions
FR-R13 Solve problems immediately	Average time to solve problems