# System Dynamics Mapping Applied to Influence Mental Models: A Case Study

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## Abstract

This paper is based on the results of experience working with a small firm, which experienced loss of key customers due to quality problems. One another large customer threatened to take their business somewhere else. These customers had been doing business with the firm for at least 10 years. It is at this point in time, i.e., Summer of 1986, the author was brought in to help the management develop a quality assurance program. After initial discussion, it became clear that the clamor for quality as found in popular and professional media did not permeate the management thinking. The expectation was to have someone install SPC charts and initiate Quality Circle activities. Ultimately, the responsibility for maintenance of these black boxes would be assigned to their Quality Supervisor. It was clear that if the plant manager and the production supervisor did not assume the responsibility by making serious efforts to develop the quality perspective and did not involve in the learning process, the probability of successful implementation would be close to zero. The paper discusses how system dynamics symbols were used to map the mental models and to provide focus for generating dialogue. There was never any need to build a full scale model.

## Introduction

In the past ten years there appears to be willingness on the part of several system dynamist to make the subject more accessible to much broader audience (Richmond 1985; Senge 1987). There have been improvements in the symbols used to map and model the systems (Morecraft 1982). New ideas drawn from behavioral science field have been adopted to capture executive knowledge (Morecraft 1983, 1985). A system dynamics methodology based procedure for system description has been developed to facilitate problem recognition, understanding and qualitative analysis (Wolstenholme and Coyle 1983;, Coyle 1983; Wolstenholme 1983). These developments enable modelers and clients of the models to gain better insight into dynamic behavior. The principle of system dynamics found in the papers cited here can be used to build maps and diagrams for system description and as attention focusing mechanism for generating dialogue. This paper reports one such application in which system dynamics diagrammatic concepts were used to help address issues, to influence thinking and seek genuine managerial participation.[1]

The paper is based on the results of experience working with a small manufacturing firm, which experienced loss of key customers and a warning from another large customer due to quality problems. These customers had been doing business with the firm for at least previous 10 years. It is at this point in time, i.e., Summer of 1986, the author was brought in to help them develop a quality assurance program. After initial discussion, it became clear that the clamor for quality as found in popular and professional media did not permeate the management thinking. The expectation was to have somebody install the necessary SPC

1 The interpretation was possible only in retrospect.

(Statistical Process Control) charts and initiate Quality Circle activities and then the responsibility for maintenance of these "black boxes" would be assigned to their Quality Supervisor. They assumed that the development and the use of SPC charts is analogous to following a step by step process, which can be mastered by anybody with some practice and hence, direct involvement by management people at the time was unnecessary. Furthermore, the author was also informed that the that the lost orders from key customers were more than made up by addition of several small orders and they expected overall demand to increase in the foreseeable future. Apparently the sense of urgency to do anything about quality was much lower compared to that few weeks back.

It became immediately clear that unless the managerial people develop a clear long term view about the business they were in and begin to view the quality assurance related activities not as a set of well defined tasks which can simply be delegated, much of the new efforts toward improving the quality would be ineffective. The paper discusses how system dynamics symbols were used to develop a big picture to aid in thought process. Much of the information was drawn from the mental models that the management people carried with them. The actual process of developing the visual representation of the feedback systems provided the focus for generating dialogue. In retrospect this process may be attributed some credit for change in the attitude and the behavior toward the quality assurance activities.

The next section briefly describes the background of the company. The following section lists the system generated problems. The paper then examines specific system dynamics diagrams developed for the purpose of bringing in a system view into discussion of issues and problems. Further fine tuning for computer based analysis was never warranted and hence, was not undertaken. The paper concludes with a brief statement of the state of nature of the same company three years later.

## Brief Historical Background of the Company

Calumet Electronics is a typical small job shop, manufacturing single-sided and double-sided circuit board. The company started in late sixty's. Printed circuit boards were in demand in early seventy's and customers used to pay good price for the boards. At the time the specifications were not tight and no stringent quality level was demanded. In response to new process technologies and demands of the customers for higher quality and tighter specifications, manufacturing facilities were upgraded by early eighties. In mid-eighties, the manufacturing facilities consisted of CNC drilling machines, new Electroless line, improved plating, etching, and soldermasking operations. The technology can easily be considered adequate enough to meet customer needs and requirements for foreseeable future.

In late seventies, a separate quality assurance department was formed to handle quality related tasks. The quality of product depended heavily on inspection and even for next several years their functions mainly consisted of performing laboratory analyses, inspection at critical manufacturing stages, customer interface, quality cost analysis and implementing corrective actions.

The net sales and profit were high in 1980 but started declining in the next three years. Business picked up again in 1984 mainly due to increased demand for circuit boards. However, customers started demanding better quality products and on time deliveries. The company started losing major customers like Motorola, Johnson Controls, and NCR. In 1986 the company had about sixty customers, the largest of these being Alan Bradely, Barber Colman

and stewart Warner. A quick analysis of backlog of orders revealed that their customers can be grouped by order size: large order customers and small order customers. The small orders were in the 25 to 50 pieces range and the large orders were of size 100 pieces or above. The customers who gave them large orders demanded higher quality, where as small orders were basically prototypes with less stringent quality and specification requirements. Engineering changes from customers and requests for waivers from the company were common for small orders. The production scheduling and control were developed around delivery promises.

Calumet Electronics employed about fifty people. The management structure consisted of four people: President, General Manager, Production Manager, and Quality assurance manager. The individual who held the position of the president was also one of the major investor and has been with the company for less than two years. There were eight supervisory people. Five of them reported to Production Manager, two reported to Quality Assurance manager, and the supervisor of the Engineering reported to both of them. The Production Manager and the Quality Assurance Manager reported to the General manager, who in turn reported to the President. General Manager also interacted with the customers. He was responsible for quoting price and the delivery dates for any new orders. In his absence, Production Manager dealt with the customers. The company also retained sales representatives who were compensated on commission basis. Established customers ordered directly. The most of the orders otherwise came through sales representatives.

Education background of all shop floor employees was limited to high-school education. All other managerial people have two years of technical education beyond high-school. Many of them have been with the company for as long as eighteen years. Most of them developed and honed their skills on the job.

**System Generated Problems**

In early 1986, due to the quality problems the company lost few large customers. However, couple of very loyal customers offered the company another chance to demonstrate that within some well defined time period the quality related problems would be addressed and resolved. They were required by one of the major customers to participate in the customer's Vendor Certification program. It is at this juncture in time the author was hired as a consultant.

After several interviews with the management personnel many problems became self -evident. The past management practices and policies were responsible for the erosion of productivity and loss of faith in quality by their long term customers.

Few specific problems identified at the time are listed below:

1. Many good initiatives were rarely executed well. For example, the company had in their possession several video tapes on circuit board manufacturing, SPC, and "employee involvement" for more than a year and the tapes were never viewed by anybody.

2. Manufacturing and quality costs were rising out of proportion. More they tried to control, worse they became. The workers were blamed frequently for the rising cost.

3. The management felt overworked taking care of day to day problems. At the time, increasing total number of small orders (mostly prototypes) compounded the scheduling and delivery performance problems.

4. Quality was perceived to have to do with the level of acceptability of the finished product and hence, major investment in the inspection technology was being contemplated. For example, a report from a major customer showed that the products from Calumet Electronics were less than five percent defectives and the company was ranked higher consistently over several reporting periods by the same customer. Ironically, very same customer demanded their suppliers to work toward Vendor Certification and the company was in a probationary status because of the quality problems. The management interpreted that all they need to do was to locate the defects much more efficiently and accurately during the inspection stages. Emphasis was on inspecting for "quality" rather than defect prevention.

5. Workers basically followed procedures developed by the management and rarely offered any suggestion for improvements.

6. The work environment did not encourage the employees to extend their knowledge beyond their own work. As a result, over time few key workers became indispensable and were in position to disrupt the work flow.

Quality assurance's importance was finally recognized, but at a time when the focus was least desired. At the moment the problem was not whether the needed tasks[2] could be successfully completed or not, but the managerial inability to understand the concept of manufacturing capability and stability and required manufacturing discipline for any quality assurance activities to continually benefit. Having more manufacturing discipline means an attitude toward and approach to work which explicitly recognizes the mutual interdependency of all functions and primary as well as higher order consequences of the interactions between the product flow and the processes. The challenge faced by the author was how to assure that independent local calculation of immediate term comfort and benefits would not weaken, if not defeat, the reasons for starting the quality assurance programs. The difficulty was that of convincing the management that the performance of the company depends more on the interactions among its connections and explicit or implicit policies set in place by management to regulate those connections, and not on the independent actions to support the quality programs. A system perspective was clearly desired for all managerial people, so they can assume responsibility by making commitment, not just espoused, to understand the role of "quality", involve in the learning process, and take responsibility for quality.

To aid in developing the required system perspective, the principles of system dynamics were used to map the mental models. The pictorial representation of the situation provided a focus to generate dialogue and discuss likely future scenarios.

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2 The quality assurance tasks identified were:

1. Analyze various types of defects and choose few for further diagnostic work to understand the underlaying causes.

2. Identify few critical processes for further study and use them as pilot work stations for later SPC demonstration.

3. Develop a SPC training program for all managers and supervisors.

4. Choose two groups of shop floor workers to demonstrate how a "brainstorming " session can be used to facilitate continuous improvement.

5. Work with the management to develop a five year quality improvement plan, which was required by one of their major customers.

The management at this time was also encouraged to hire one of the graduate students to assist in carrying out various investigations, data collection, and pilot SPC demonstration.

## System Dynamics Flow Diagrams

Out of the initial discussion, it was established that the management had difficulty understanding the relationship between the quality image and long term customer demand and the role of manufacturing process capability and stability in their production environment. After piecing together some requirements for one Vendor Certification Program, the firm was expected to participate, the perceived quality image by the customers was equated to having the manufacturing processes capable and stable. Three interrelated decision making sectors were identified. The market sector generated orders along with technical and delivery requirements and received in turn some negotiated delivery quotes. The order entry sector, which for Calumet Electronics was a single person operation made price and delivery quotations for the customers and passed the order information to the production sector. The production sector planed the orders and made sure that the orders were shipped on time and simultaneously transmitted the quality image to the customers. The quality image typically reflected not only the firm's process capability and stability, but a clear indication of the firm's ability to produce circuit boards on time, at low cost and with high quality level. Some customers made the assessment of the quality image after the circuit boards were partially assembled and tested. The feedback from the customers in the case of significant quality problems was in the form of no more orders or a warning to Calumet Electronics.[3]

*Market Sector*

The relevant structure of the market sector is shown in Figure 1. The market could be viewed as made up of two types of customers: small order customers and large order customers. Small order customers placed an order of anywhere between 20 to 50 circuit boards and were mostly prototypes. Engineering drawing accompanying a prototype purchase order was in general not complete and had to be verified. Because of the nature of the product, frequently some engineering specifications could be waived to accommodate any processing problems. The yield was erratic and high level of scrap and rework would be expected. The marginal revenue from these type of products had always been good. The firm rarely lost any money on these products.

The large customers, mainly original equipment manufacturers (OEMs), placed orders of size 100 and above and expected technical and delivery performance as negotiated. The demand from these customers was critical from long term perspective, because of frequency with which they placed orders. The customers still doing business with Calumet Electronics were divided into two levels: satisfied customers and unsatisfied customers. The large customers had clout in the industry and were in the process of implementing Quality Assurance programs themselves. Most of them were in various stages of instituting Vendor Certification Programs. The unsatisfied category assumed to be farther ahead. However, they did put this firm in a probationary status. The firm also received explicit instructions how to become certified and hence, be a long term supplier. One of the expressed objective by the management was to become certified.

The perceived quality image by OEMs in the context of the Vendor Certification Program was assumed to be represented by the firm's manufacturing process capability and stability. The small customers themselves never explicitly cared whether or not the company had any quality assurance program. However, they were sensitive to the quality image as

3 One major OEM billed Calumet Electronics couple of times for receiving defective boards for the original price plus the cost added up to the point where the boards were tested to be defective.

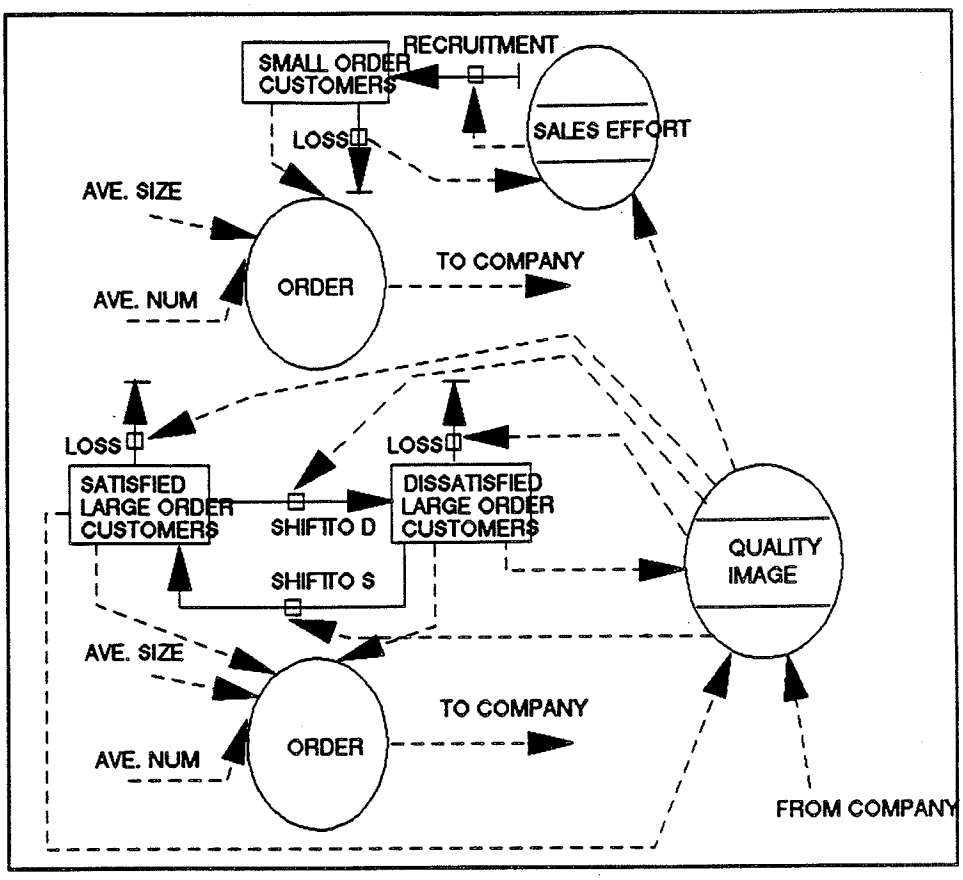


FIGURE 1: MARKET SECTOR

| | | FIRM: COOPERATE | FIRM: DEFECT |
|---|---|---|---|
| UNSATISFIED CUSTOMER: COOPERATE | | R(C),R(C) REWARD FOR MUTUAL COOPERATION | S(C),T(D) SUCKER'S PAYOFF, AND TEMPTATION TO DEFECT |
| UNSATISFIED CUSTOMER: DEFECT | | T(D),S(C) TEMPTATION TO DEFECT AND SUCKER'S PAYOFF | P(D),P(D) PUNISHMENT FOR MUTUAL DEFECTION |

FIGURE 2: THE PRISONER'S DILEMMA

expressed through composition of customers the firm was doing business with. Hence, the sales pitch by their sales representatives always mentioned the names of various OEMs to enhance perceived image of the firm.

Because the dissatisfied customers were still placing orders, the management had difficulty assessing how long they could expect their business and how much time the firm had to establish the quality credentials. The management stated during one meeting that they could convert the dissatisfied into satisfied customers by providing price breaks, creating finished inventory for prompt delivery and through improved inspection, which they could accomplish by investing in a high tech inspection equipment. It was at this point the concept of "The Prisoner's Dilemma" (Axelrod 1984) was introduced to explain possible behavior of their major unsatisfied customer. Refer to Figure 2. The customer represented one player and Calumet Electronics was the other player. The choice by either player was to cooperate or to defect without knowing how the other player is likely play. The unsatisfied customer's cooperative play was equated to giving orders to Calumet Electronics and Calumet Electronics cooperative play was equated to demonstrating that their manufacturing processes were capable and stable. The firm might be tempted to defect if the customer cooperated. The question was how long the firm could defect and still would expect the customer to cooperate. Through this play it was shown to the management that the only way both parties could win was by cooperating. The management also realized that to improve the quality image as interpreted by their unsatisfied large customers was in their long-term interest.

*Order Entry Sector*

The order entry sector has only one behavioral process and that was the interaction with new customers. The interaction process involved quoting prices and the delivery dates. A typical lead time maintained at the time was somewhere between five weeks to twelve weeks and heuristic involved took into account current backlog. Higher the current backlog, higher would be the quoted lead time. The relevant system structure is shown in Figure 3. This process was identified as a candidate project for developing computer based system for pricing and maintaining database for all existing backorders. Significant amount of time was spent by the plant manager completing each request and generating purchase orders from the customers.

*Production Sector*

The manufacturing process is defined to be machines, human labor, and the organization of work brought together to satisfy the customer needs. The long term viability and manufacturing competence is intrinsically tied to how one manages this process. After few information gathering meetings with Production Manager and Quality Supervisor, it was learned that the interaction between the product flow and manufacturing resources were basically controlled by two basic behavioral processes: 1) production planning and 2) expediting and fire-fighting.

To minimize attention diverting details, the manufacturing processes were divided into three stages: 1) initial engineering, 2) production (value adding operations), and 3) inspection (quality verifying operations). The job orders were in general supplied with engineering information (art work) and in some cases with the NC tapes for hole drilling. The engineering verification of the quality of information was a necessary step. It is at this point the routing of the job was established. A typical job lot moved through various processes and at critical points inspection was applied. The completed orders, if found to be satisfactory were shipped to the customers. Any rework or additional work due to scrap was rescheduled. Many technical details are not relevant for this paper and hence, are omitted.

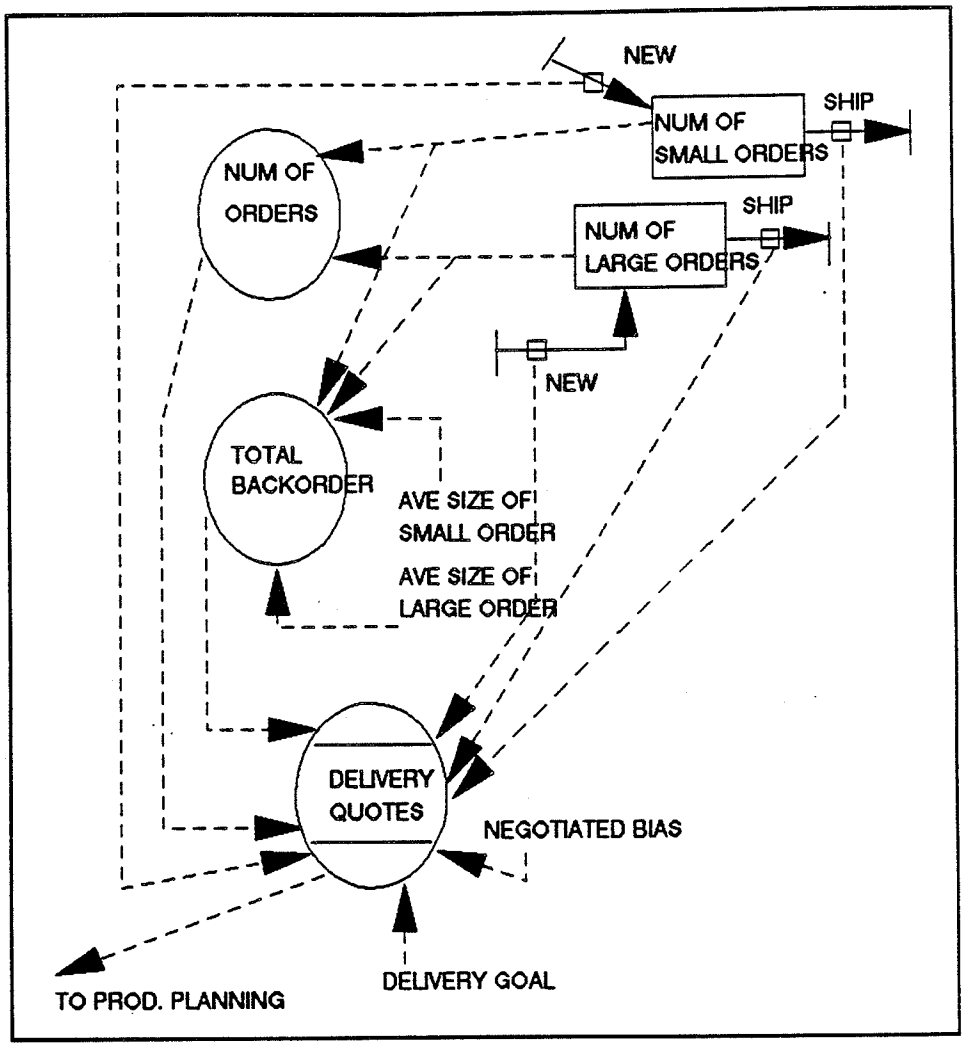


FIGURE 3: ORDER ENTRY SECTOR

In order to understand the underlying behavioral processes, two variables - the discrimination ability of quality inspectors and the process capability and stability- were added. At Calumet Electronics the shop floor was managed by what appeared to be two independent behavioral processes mentioned above. The production planning process scheduled the new orders and any rework and the expediting and fire-fighting processes assured that the orders were shipped on time and functioning of all machines. These processes directly or indirectly influenced the process capability and stability and the discrimination ability of the quality inspectors. The complete structure is shown in Figure 4.

The production planning process basically scheduled release of the material and necessary paper work to the shop floor. The negotiated due dates provided required priorities for various jobs. To account for anticipated scrap and quality problems, the job lot size was usually increased by 10 to 25 percent.

On a typical day the managers and supervisors assured the "proper" functioning of all of the processes. The term "proper" was never well defined. Only interpretation that one could make was that as long as the process was not stopped due to any malfunction, it was considered "proper". The attitude reflected here was "don't fix it, if ain't broke." Workers neither assumed the responsibility for any defects nor in some cases they had means to detect any defects. The attitude was that if there were defects, the inspectors would catch them.

Expediting was common, as due dates for the jobs came closer or missed or a customer requested status of the order, pressure was generated on the workers to speed up and the quality inspectors were asked to work faster. Overtime scheduling for the inspectors was very common. The obvious problems were that the process capability and stability got adversely affected and many more defective products were passed on to the customers. The quality inspector were capable, but their ability to discriminate defects was generally affected by the monotonous work, overtime, and the pressure from the piled up inventory and the managers. The management was aware of this problem and to remedy it they were looking into buying an automatic inspection equipment costing over $400,000. They viewed this investment as an answer to many of their problems with OEM customers.

The system view became helpful in generating various scenarios. The relationship among discrimination ability of the inspectors, the process capability and stability, fraction defectives prior to inspection, rework and scrap, delivery performance and the behavioral processes of delivery quotations, production planning, and expediting and fire-fighting provided enough material for discussion. The bayesian decision making was also introduced to explain possible effect of SPC and problem solving on defectives which could be passed on to the customers.

## Conclusion

This paper illustrated that the system dynamics concepts can be useful even if the intentions are not necessarily to develop a full blown dynamic model. If the objective is to develop just a pictorial map to present all essential decision making processes in an interconnected manner, the symbols used to draw system dynamics flow diagrams can be very functional.

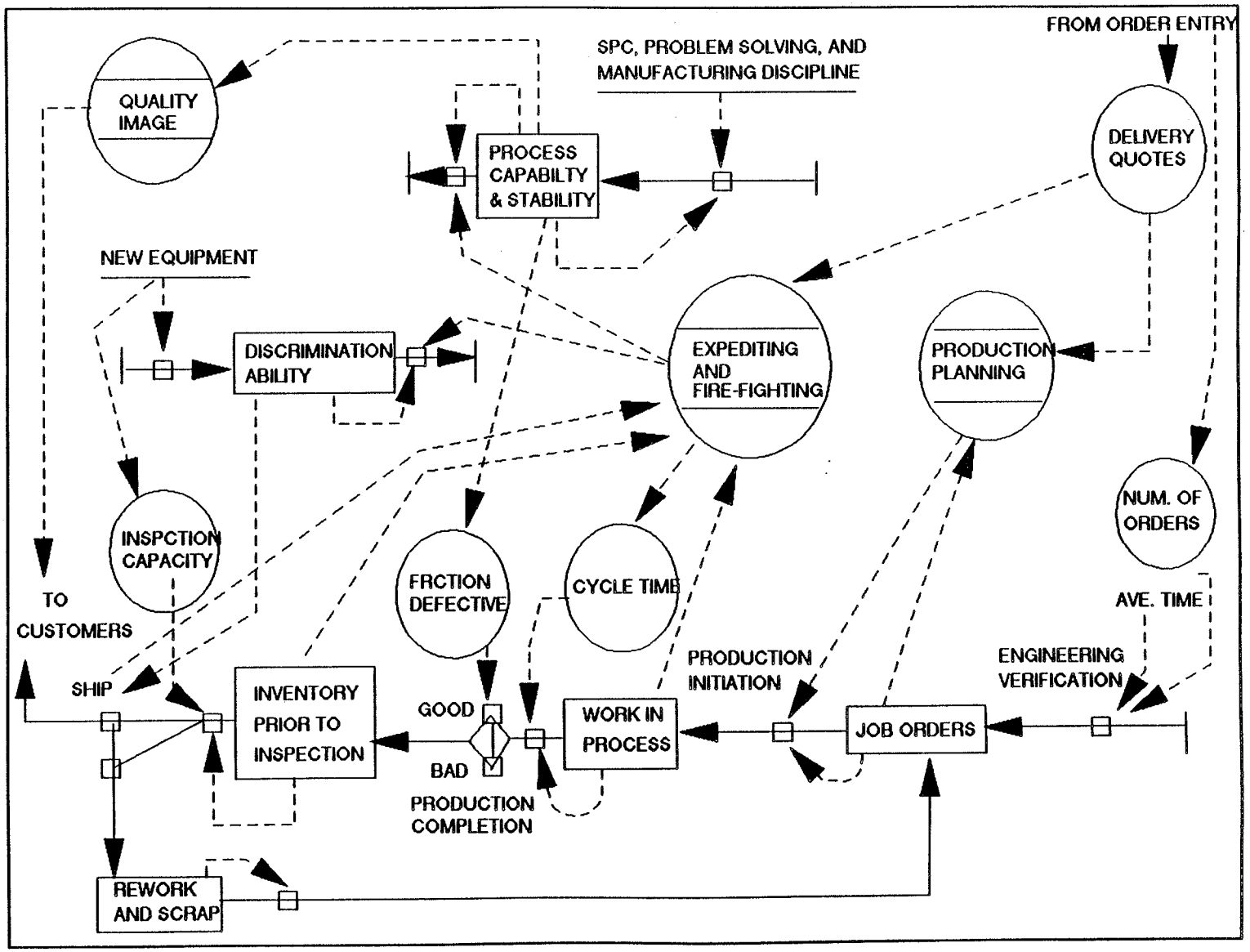


FIGURE 4: PRODUCTION SECTOR

Today Calumet Electronics has well developed quality management programs. The customer base has been expanded in last three years. Couple of times they had to turn down some customers. Several workers have been sent for variety of different types technical training programs. The average wages are much higher. Every manager has personal computer access and the company has also established a local area network. Computer based delivery and price quotation system has improved the customer interface effectiveness. The graduate student who assisted in collecting and analyzing data was hired to work there full time after his graduation. They have still long ways to go, but they no longer need any outside help.

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